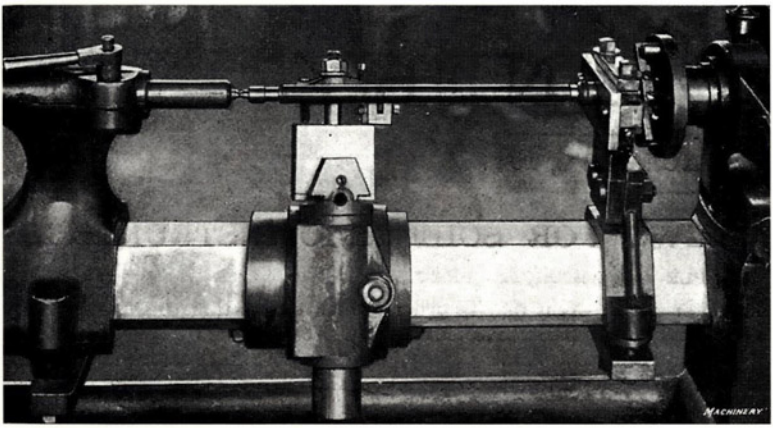


Precision Lead Screws, Gears, and Pantographs

Machinery's Industrial Secrets

Selected articles from early issues of Machinery Magazine revealing secrets of manufacturing.

reprinted by Lindsay Publications Inc

Cutting Instrument Gears

Production of Small Gears by Means of Hand-operated and Automatic Machines of the Formed-cutter and Hobbing Types – First of Two Articles

MACHINERY MAGAZINE – APRIL 24, 1924

Gears of the small precision class used for various kinds of measuring and recording instruments, pressure gauges, meters, vending machines, clock mechanisms, etc., are produced by three general methods, the selection of which depends upon the size of the gears and the quality desired. One method is to form the gear teeth by some cutting process such as milling or hobbing; another is to use a sub-press die; and a third method is to form the teeth by a drawing process, as applied to the production of pinions in rod form.

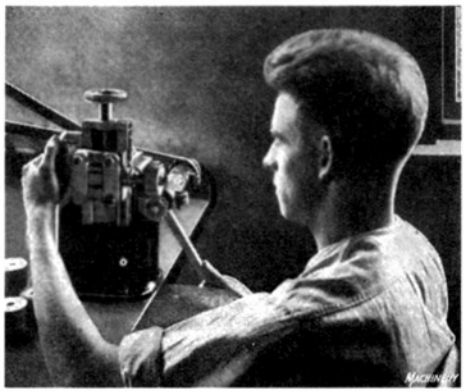


Fig. 1. Cutting a Stack of Small Gears on a Hand-operated Machine

When the teeth are milled it is common practice to use a die for cutting the plain blanks from flat stock of the right thickness. These diecut blanks may or may not be turned before the teeth are cut, the practice varying for different classes of work. Many gears, especially if small and quite thin, are placed in the gear-cutting machine just as they come from the dies; but when comparatively thick stock must be used, the

Machinery's INDUSTRIAL SECRETS
Selected articles from early issues of Machinery Magazine revealing early manufacturing methods.
Precision Lead Screws, Gears, and Pantographs
reprinted by Lindsay Publications Inc – all rights reserved
1999 – ISBN 1-55918-232-6 9 8 7 6 5 4 3 2 1

Fig. 2. Rapid Method of turning Small Instrument Gear Blanks

die-cut blanks are often turned to size, although in either case the blank may be left slightly oversize in order to allow for a "topping cut." In other words, there is a slight allowance on the blank diameter to permit finishing the tops of the teeth in the gear cutter. This practice is quite common in cutting precision gears for instruments, meters, and similar classes of work.

Small precision or instrument gears that have the teeth formed by a cutting process are cut either on machines using a formed cutter, the shape of which is reproduced in the gear tooth, or on machines of the generating type, using hobs. The machines using formed cutters may be controlled by hand or may be automatic.

While different designs of automatic and semi-automatic machines have been developed for cutting small precision gears, it is the practice at one large plant to use hand operated machines for cutting most of the precision gears. These machines are simple in design, and by their use gears can be cut very rapidly, notwithstanding the fact that the machines are hand controlled.

A general view of one of these machines is shown in Fig. 1. The gear (or stack of gears) to be cut is carried by a spindle having at the rear end an index plate *A* (see Fig. 3) with notches corresponding to the number of teeth required. This spindle is mounted in a quill, which, in turn, is clamped in a V-shaped groove on vertical slide *B*, which provides adjustment to suit the gear diameter and depth of cut. This vertical slide also has lateral adjustment to permit centring the work relative to the cutter and it is carried by a main slide which can be moved at right angles to the axis of the cutter spindle by a hand lever. The cutter spindle is supported by a fixed bearing, and is driven by belt from a countershaft at the rear of the machine.

When this machine is in use, the operator feeds the blank (or blanks) across the cutter by the hand lever on the right-hand side, and after each tooth space is milled and the slide with-

Fig. 3. How Indexing is controlled by Hand on Machine in Fig. 1

drawn, the work spindle is indexed to the next notch by using the left hand. The method of holding the work depends upon its shape. For instance, small instrument pinions cut integral with a staff or shaft would be cut one at a time while held between some kind of supporting centres. On the other hand, flat blanks would be stacked on an arbor to permit cutting quite a number in one operation. The hand-controlled feeding and indexing movements are executed so rapidly that a high rate of production is obtained, as indicated by the following specific examples of gear-cutting practice on these machines.

Examples of Precision Gear Cutting

All these pieces were machined on the hand-operated machine just referred to, and they illustrate in a general way not only the variety of gear cutting done on these machines, but the rates of production for different classes of work. Gear *A*, Fig. 4, has 60 teeth, of 36 diametral pitch, and is cut at the rate of 100 per hour. Gear *B*, which is used in a meter, has 20 teeth and is cut at the rate of 300 per hour. This gear is made of No. 16 gauge stock. Gear *C* has 26 teeth, of 52 pitch, and a 1/8-inch face. The cutting rate is 250 per hour. The escapement wheel shown at *D*, which is 1 inch in diameter and has 30 teeth cut in it, is turned out at the rate of 250 per hour.

It will be understood that in most cases several blanks are cut at the same time, although this is not always practicable, as shown by some of the examples to follow. Pinion gear *E* has 18 teeth, of 32 pitch, and 180 pinions are cut per hour, five being placed on the arbor at one time. Pinion gear *F* has six teeth, of 24 pitch, and is cut one at a time at the rate of 140 per hour. Pinions of the type illustrated at *G*, *H*, and *I* are cut one at a time. Pinion *G* has 13 teeth, of 125 pitch, a 5/32-inch face width, and the cutting rate is 150 per hour. Pinion *H* has 18 teeth, of 90 pitch, a 3/16-inch face, and is cut at the rate of 100 per hour. Pinion *I* has 16 teeth, of 64 pitch, and is cut at the rate of 100 per hour.

In cutting the segment gears *J*, ten are placed on one arbor. These segments have 21 teeth, of 48 pitch, and are made of No. 11 gauge stock. The rate of cutting is 100 per hour. The nickel-silver racks *K* are cut five at a time, at the rate of 80 per hour. These rack teeth have a linear pitch of 0.049 inch. An example of very fine gear cutting is shown at *L*, the gear teeth being only 150 diametral pitch. These segments are cut at the rate of 260 per hour. Segment gear *M* has 22 teeth, of 64 pitch, and the rate is 300 per hour.

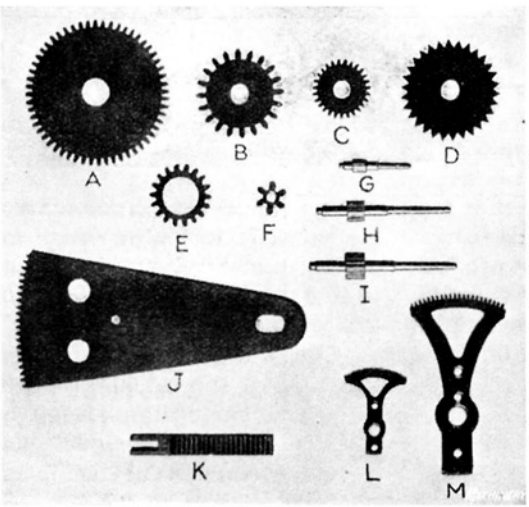


Fig. 4. Samples of Instrument Gears cut on Hand-operated Machines

Special Machines for Turning Small Gear Blanks

The special type of lathe illustrated in Fig. 2 is used at the plant previously referred to for turning small gear blanks prior to cutting the teeth. These small lathes are exceedingly simple in their arrangement, but they make it possible to obtain a very large production. The gear blanks, as they come from the dies, have holes in the centre, and are slightly larger than the correct outside diameter. Fifteen or twenty blanks are inserted over a projecting end of the lathe spindle, and a nut is screwed on to hold them together. The driving belt is then shifted, and as the blanks revolve rapidly they are turned by means of a hand-operated cutter bar.

This cutter bar *A* is simply a tube containing a small cutting tool, which extends outward far enough to turn the blanks to the correct size when the bar is pushed along the Supporting members *B*. As will be seen. the bar rests against vertical faces on these fixed supports, so that the cutter, which. bears on an additional support *C* near its outer end, is always in the same position. After a stack of blanks has been turned, this cutter bar is placed on the bench, so that it will not interfere with the removal of the finished blanks and the reloading of the spindles. As soon as a new stack of blanks is in place, the cutter bar is again placed on its supports, and as it is pushed along parallel with the lathe spindle the blanks are rapidly turned to size.

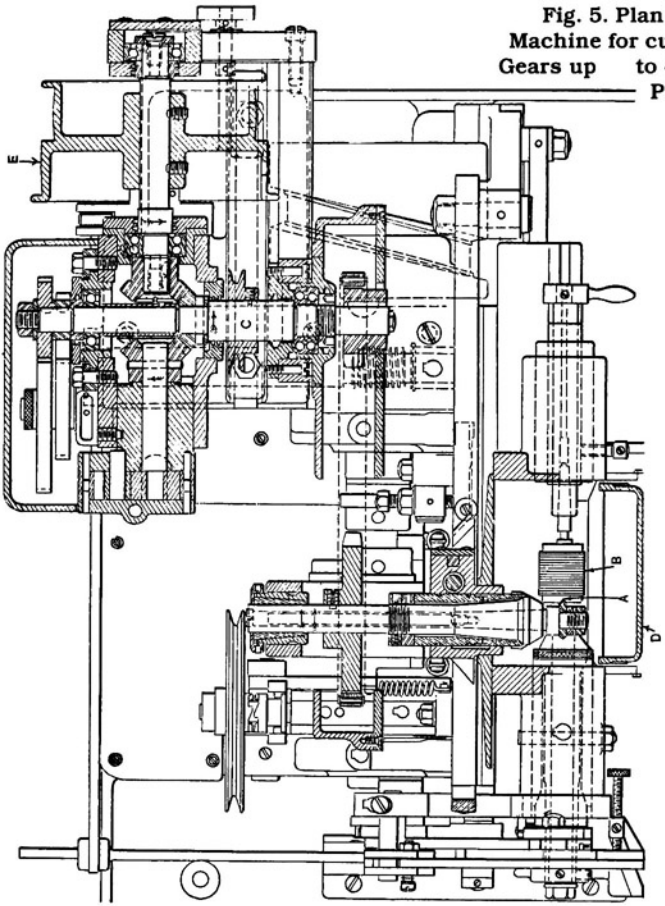


Fig. 5. Plan View of Machine for cutting Spur Gears up to 4 inches Pitch Diameter

An idea of the rate at which blanks can be turned on this simple machine may be obtained from the following examples: Brass blanks for meter gears 15/16-inch in diameter, made of No. 16 gauge stock, are turned at the rate of 600 per hour. In doing this work fourteen blanks are placed on the arbor at one time. Blanks 5/8-inch in diameter, made of No. 8 gauge stock, are turned at the rate of 500 per hour, six blanks being placed on the arbor at a time. This machine does not only rapid but also accurate work.

Automatic Machines for Cutting Small Gears

Machines of the automatic or semi-automatic types have been widely used for cutting small gears in watch and clock factories, and by manufacturers of meters, recording instruments, and various other kinds of apparatus requiring gearing of

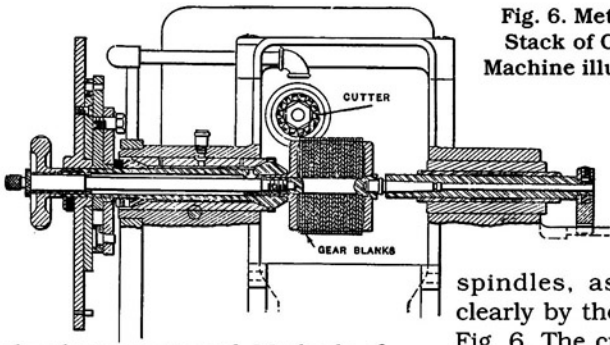


Fig. 6. Method of holding Stack of Gear Blanks on Machine illustrated in Fig. 5

the class mentioned. Methods of using some of the machines built by the Waltham Machine Works, Waltham, U.S.A., are described in the following: Fig. 5 shows a plan view of a semi-automatic machine for cutting spur gears up to 4 inches pitch diameter with diametral pitches of 16 and finer. This machine is so designed that the movements of the slides and the indexing are automatically controlled, and are continued until the machine stops after completing the last cut. The insertion or removal of the work, however, is done by hand, so that the machine is not fully automatic like some of the types referred to later. This machine is of the formed-cutter type.

Referring to Fig. 5, the cutter may be seen at *A*, and ordinarily a stack of gear blanks *B* is held on an arbor supported by two spindles, as shown more clearly by the detailed view, Fig. 6. The cutter spindle is driven from shaft *C* (Fig. 5) by a silent chain transmission. A feeding movement is imparted to the work slide by means of a cam which gives a quick return. The position of the work slide relative to the cutter can be changed readily by means of a rack and pinion adjustment. During the return stroke, and while the work is being indexed the cutter-spindle slide is elevated automatically, and this slide is clamped automatically during the cutting stroke. Vertical adjustments of the cutter slide for

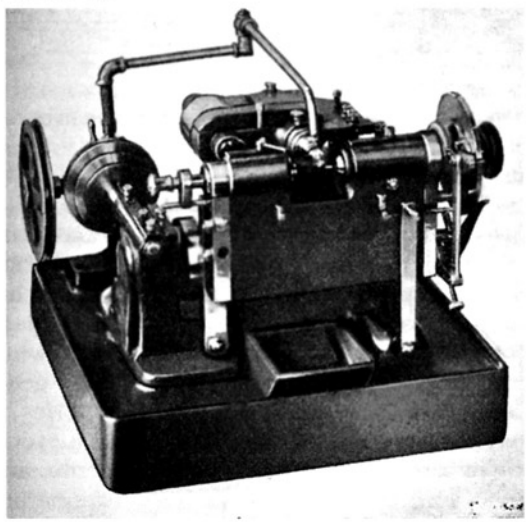


Fig. 7. Type of Gear-cutting Machine designed to meet Requirements of Watch Factories

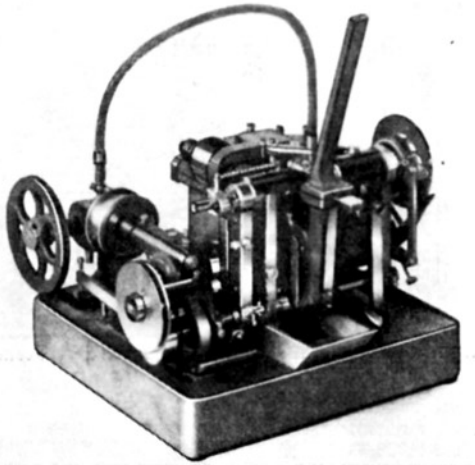


Fig. 8. Automatic Gear-cutting Machine equipped with Magazine Feeding Attachment

regulating the depth of cut are controlled by a handwheel graduated to thousandths of an inch.

The front bearing of the cutter spindle is threaded on the outside, and is rotated for centring the cutter relative to the work. A hinged cover *D* on the work slide completely encloses the cutter and work. The positive indexing movement is controlled by one revolution of a camshaft, which is idle except when indexing. The index plate may be seen at the left of the work spindle in Fig. 6. While the index mechanism may be arranged for obtaining different divisions, it is considered advisable, for manufacturing purposes, to use one index plate for each number of divisions required.

The sprockets for the chain drive to the cutter spindle are of different diameters and are interchangeable, so that either one may be used as a driver to vary the cutting speed. Additional changes are obtained by means of the stepped cone pulley *E*, Fig. 5. Speeds of 300 and 375 revolutions per minute are used for steel work, and 1,200 and 1,500 revolutions per minute for brass. For cutting tool steel of average quality and temper, a feed of 4 inches per minute is about right. For soft steel the feed should be increased to about 7 inches per minute, for bronze to 15 inches per minute, and for brass to 20 inches per minute. These speeds and feeds are based on the use of a high-speed steel cutter 1 1/4 inches in diameter.

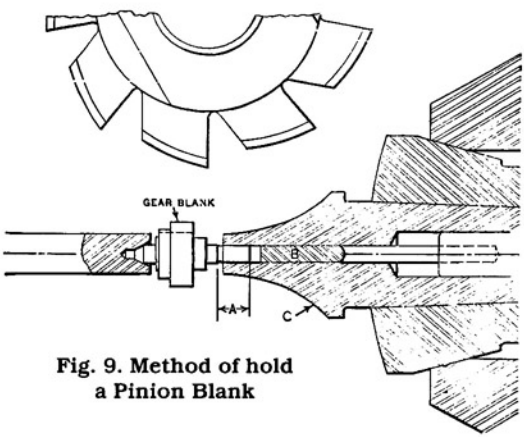


Fig. 9. Method of hold a Pinion Blank

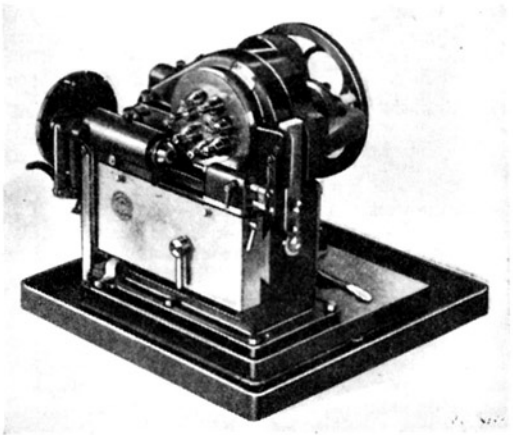


Fig. 10. Machine used for cutting Teeth of Watch Escapement Wheels

Machine Equipped with Roughing and Finishing Cutters

The gear-cutting machine shown in Fig. 7 is one of a line designed to meet the requirements of watch factories, etc. This particular machine is arranged for cutting pinions. The cutter spindle is equipped with three cutters, two for roughing and one for finishing. The finishing cutter is nearest the front bearing and in the most rigid position. The cutter spindle is shifted automatically for locating each of the three cutters in the working position. This machine is intended particularly for cutting steel pinions of 48 diametral pitch or finer. A similar machine equipped with a magazine feeding attachment is illustrated in Fig. 8. This machine is, of course, fully automatic in its operation, the blanks being automatically brought into the cutting position by the magazine feeding attachment.

Machine having Seven Cutter Spindles

The machine shown in Fig. 10 is used for cutting the teeth on the escapement wheels of watches. It has seven cutter spindles, and each one carries a cutter of a different shape. The indexing of the turret, which contains the seven spindles, is automatically controlled, so that all operations are continuous after the work is placed in position. The spindles have screw adjustments for varying both the depth of cut and the location longitudinally, as some of the cuts are in a central position and others off centre.

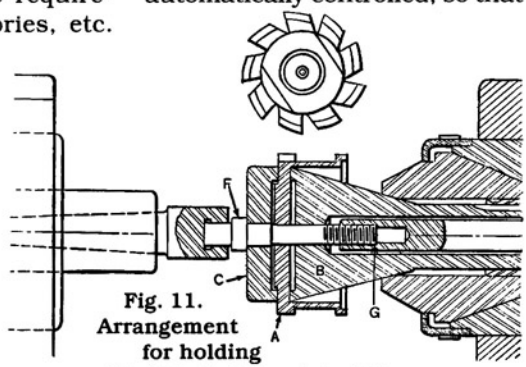


Fig. 11. Arrangement for holding Steel Spring Barrel A while cutting Gear Teeth

Methods of Holding Small Gears for Cutting

The type of work-holding arbor illustrated in Fig. 6 is recommended for use in connection with the 4-inch machine shown by the plan view, Fig. 5. The arbor holds a stack of blanks between two flanges that are nearly as large as the root diameter of the gears to be cut, thus providing rigid support. Figs. 9, 11, 12, and 13 show various methods of holding pinions and gears on machines of the class shown in Figs. 7 and 8. These same methods, however, may be applied equally well on larger machines.

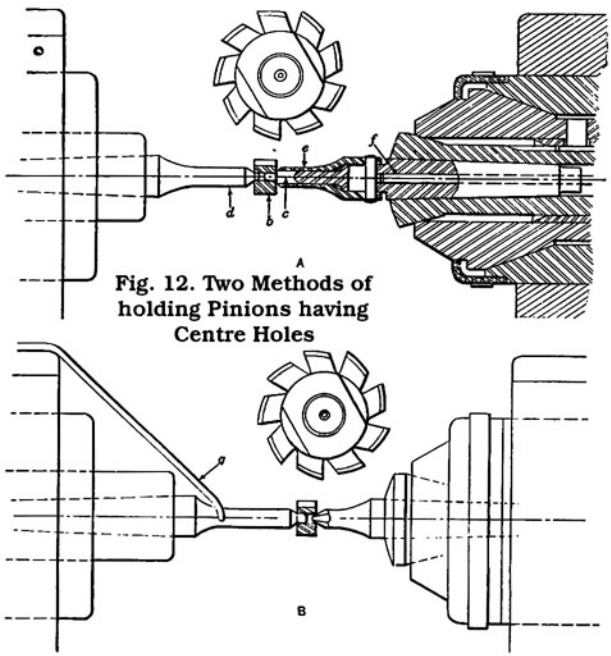


Fig. 12. Two Methods of holding Pinions having Centre Holes

Fig. 9 shows how a pinion is held to ensure cutting the teeth concentric with the pivots. The tapering section marked *A* is not a part of the finished pinion, but is merely used for holding the blank while the teeth are being cut. The opposite end is supported by a conical centre in the tail spindle. Machines operating on work of this class should be equipped with a magazine feeding mechanism. The rod *B*, within the head centre *C*, is used as an ejector.

Holding Hollow Pinions

Two methods of holding hollow pinions on automatic pinion-cutting machines having magazine feeding mechanism are illustrated in Fig. 12. Referring to the upper view *A* in this illustration, the hollow pinion blank *b* is pushed on a slightly tapering centre arbor *c* by the tail centre *d* in order to hold it firmly in place. The finished pinion is removed from the tapering arbor by the ejector sleeve *e*, having a cross pin that is engaged by ejector rod *f*.

The lower diagram *B* shows a hollow pinion blank which is centred by the tailstock centre and forced against a headstock centre having corners that act as a driving dog for indexing the

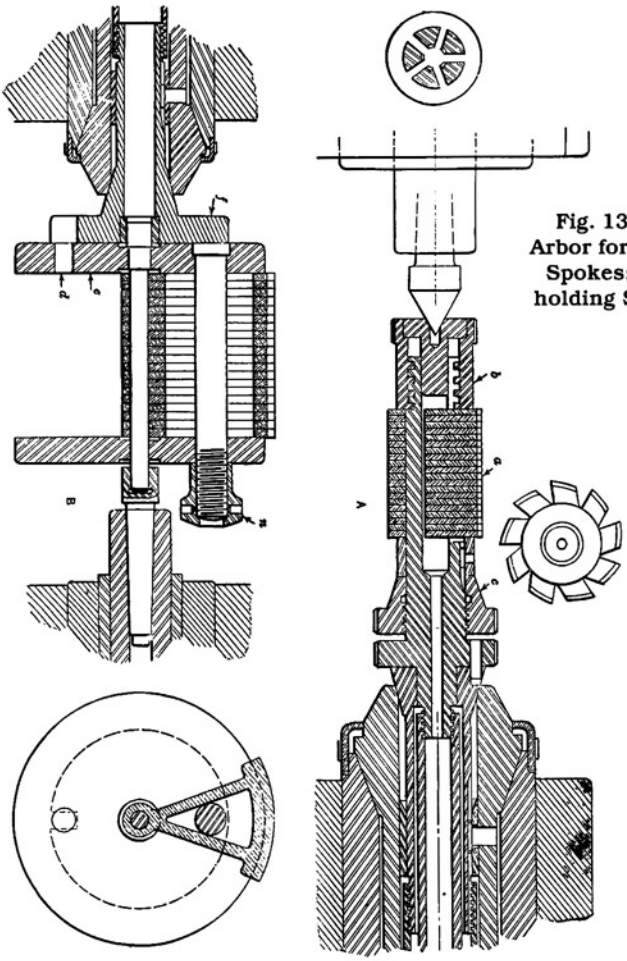


Fig. 13. A–Segment Arbor for Blanks having Spokes; B–Method of holding Segment Gears

pinion blank. When the tail spindle is withdrawn, the finished pinion comes against a stripper *g*, which strips or pushes the pinion off the centre.

Holding a Steel Spring Barrel

In Fig. 11 is shown a method of holding a steel spring barrel while cutting the gear teeth on an automatic machine. The spring barrel *A* is held firmly against the end of chuck *B* by clamp *C*, which, in turn, is tightened by means of arbor *F* and draw-in screw *G*. The outer end of arbor *F* is supported by the tail centre.

The upper diagram *A*, Fig. 13, shows a design of segment arbor such as is used for blanks with spokes. As the sectional view to the left shows, the seg-

ments of the arbor are between the spokes and hold the blanks by the inside of the rim. The stack of wheel blanks *a* is held between the nut *b* and the clamping nut *c*. Two arbors should be used to permit loading the blanks on one while the other is in the machine. When the arbor is to be loaded with blanks, clamping nut *c* is first turned back against the arbor shoulder, and nut *b* is removed. After sliding the blanks on the arbor, nut *b* is screwed against the shoulder at the slotted end of the arbor, and then nut *c* is tightened against the stack of blanks. These wheel blanks are without centre holes, and a formed cutter is used to trim the tops of the teeth at the same time that the sides and root are finished. The gears are afterwards held by the outside in order that the centre hole may be located accurately relative to the teeth.

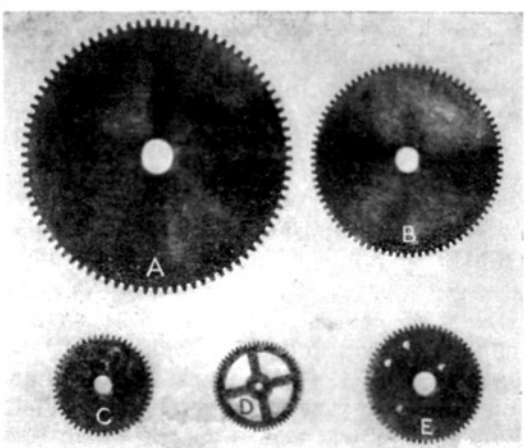
Holding Sector-shaped Blanks

Diagram *B* shows a method of holding sector-shaped blanks. The face plate *f* has a pin or dog *d* engaging plate *e*. The blanks are clamped between this plate and the one on the opposite side by nut *n*. The clamping stud and arbor locate the blanks (see end view), and the dog locates the holding device. The index plate of the machine is set in relation to this locating dog. A duplicate work-holding device should be used to permit loading one while the machine is operating on work in the other.

Cutting Instrument Gears

Application of the Hobbing Process and Production of Small Pinions in Rod Form – Second of Two Articles

MACHINERY MAGAZINE – MAY 29, 1924



The gear-bobbing machine illustrated in Fig. 14, which is made by the Meisselbach-Catucci Manufacturing Co., U.S.A., is especially designed for cutting the gears and pinions in meters, gauges, clock movements, etc. While this machine is intended primarily for cutting spur gears, worm gears can also be cut

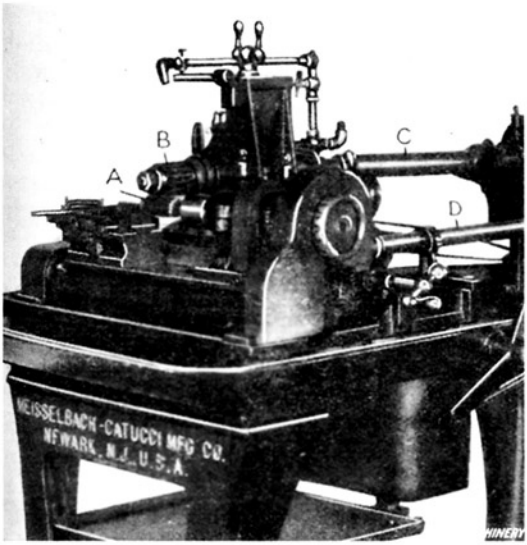


Fig. 14. Hobbing Machine use for cutting Instrument Gears

on it by using a hand feed. The illustration shows the machine hobbing spur gears. A stack of gear blanks *A* is placed on the arbor, this being the usual method whenever practicable. The hob *B* is rotated through shaft *C*, having universal joints to permit a feeding movement for the hob. Change gears at the rear of the machine drive shaft *D*, which in turn revolves, through suitable gearing, the work spindle, and through additional gears and shafts, the feed screw for the hob slide. In setting up the machine, the required speed ratio between the hob and work is obtained by the change gears at the rear.

When the hob has finished its cut across the stack of gear blanks a stop is reached which releases a half-nut engaging the feed screw, thus stopping the feeding movement. At the same time the driving belt is shifted to the idler pulley, so that the hob stops revolving and the flow of cutting oil or compound also discontinues, which facilitates removing the work and inserting another lot of uncut blanks. After the half-nut has been disengaged, the hob slide can be returned to the starting position rapidly, simply by sliding it along the ways by hand instead of turning the feed screw. As the actual cutting time is very short on most of the work handled on a machine of this kind, it is essential to reduce the idle time between cuts to a minimum. That is why provision is made for the rapid hand adjustment of the hob slide.

While the output of a gear-cutting machine, as well as of any other machine tool, varies widely for different classes of work, the following specific examples illustrate in a general way what has been done on the type of machine shown in Fig. 14. Brass spur gears having 90 teeth of 80 diametral pitch were hobbed at the rate of 240 per hour. This rate is not given as representing unusual production, but the output for certain instrument gears of good quality. These gears were 0.020-inch thick, and in cutting them, 100

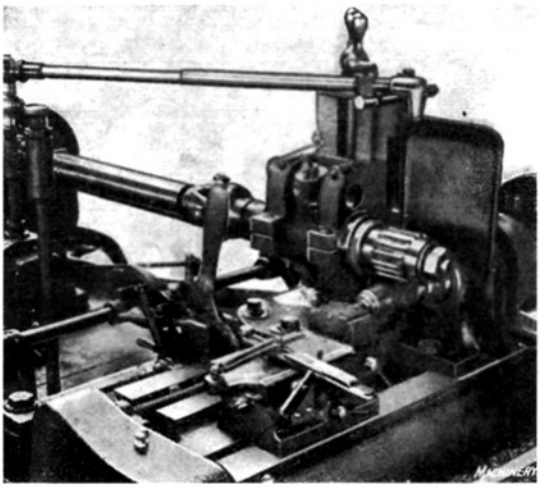


Fig. 15. Hobbing a Stack of Thirty-five Water-meter Gears

were placed on an arbor at the same time.

As the gears have spokes and a hole in the centre which is small in proportion to the gear diameter, a special arbor was used. Instead of using a very small arbor which simply passes through the centre holes, this special arbor has segments that fit between the spokes, in addition to a small central spindle for the holes. This type, which holds the work more securely and increases production, will be illustrated later in connection with another gear-cutting operation.

Another example of work is the cutting of steel spur gears having 18 teeth of 18 diametral pitch. These gears have a face width of 3/8-inch, a 1/2—inch hole, and a long shoulder, so that only two can be cut at a time; consequently, the production in this case is five minutes per gear, or twelve gears per hour.

Some instrument gears cut at the plant of D.S. Plumb, by the hobbing process, are shown in the heading illustration. These are all brass gears, and a Meisselbach-Catucci hobbing machine was used for cutting the teeth. Gear *A* has 84 teeth of 24 pitch, and is made from No. 11 gauge stock. Twenty blanks are placed on an arbor and cut simultaneously. The production rate is 100 per hour. Gear *B* has 80 teeth of 26 pitch, and the rate of production on this job is 120 gears per hour, 20 being placed on one arbor. Gear *C* has 50 teeth of 40 pitch, the production rate being 200 per hour. This gear is made of No. 13 gauge stock. Gear *E* has 60 teeth of 40 pitch, and the blanks are made of No. 13 gauge stock. Twelve are placed on one arbor, and the production rate is about 144 per hour.

An interesting example of rapid gear cutting on the Meisselbach-Catucci machine is shown in Fig. 15. This machine is cutting brass spur gears for water meters. The gears are like the sample shown at *D* in the heading illustration; they have 60 teeth of 52 diametral pitch, and are made of No. 18 gauge stock. Thirty-five are placed on an arbor at one time, and the production is about 500 per

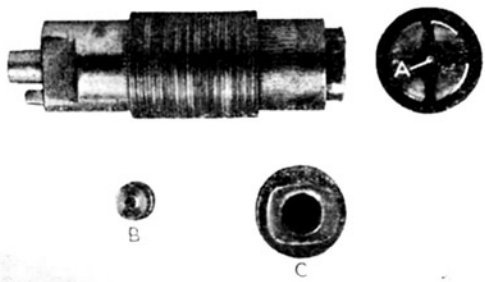


Fig. 16. Segment Arbor used for Operation illustrated in Fig. 15

hour. This gear-cutting operation illustrates the use of the segment type of arbor, which is made to pass between the spokes of the wheel as well as through the central hole. One of these arbors loaded with gear blanks is shown in Fig. 16. An endwise view of another similar arbor is shown at the right-hand side of this illustration, the clamping nut having been removed, to show how the arbor segments fit between the spokes of the gear blanks. The blanks are centred by a pin *A*; this pin, in turn, is accurately located by the hole in plug *B*, which is pushed over pin A before screwing on clamping nut C. This sleeve nut screws over the ends of the segment-shaped arbor sections and bears against the outer gear blank rim, thus holding the blanks rigidly. The gear blanks are not turned, but are placed in the gear hobber just as they come from the blanking die. This die cuts the blanks slightly over-size, and the hob takes a light cut over the tops of the teeth, thus finishing all of the tooth surfaces.

While all the examples of instrument gear work previously referred to represent cut gears, it will be understood that a great many small gears for use in clock mechanisms and various other classes of instruments are produced by means of subpress dies. Cut gears are preferable for accurate work, although very accurate gears are produced in well-built sub-press dies, pro-

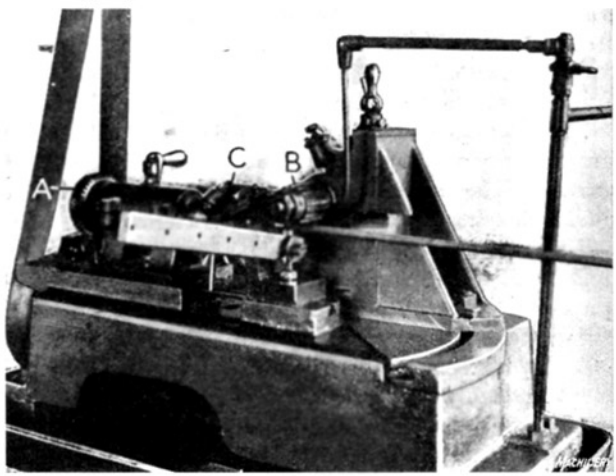


Fig. 17. Special Machine for cutting Pinion Rod by Hobbing Process

vided the thickness of the stock is not excessive.

Making Small Pinions in Rod Form

Many small steel and brass pinions are produced by first making the pinion in rod form and then cutting the rod into whatever lengths are required for the pinions. In other words, the teeth are formed along the rod, which may have a length of 3 or 4 feet. The companies making pinion rod usually sell it in rod form, and the manufacturer using the rod cuts it into short pinion lengths. Either a hand screw machine or an automatic is generally used for this purpose, the machine being employed to cut whatever shoulders, holes, or bearing surfaces are required for the pinion. The teeth on pinion rods may be formed either by a cutting process or by drawing plain rod through suitable dies.

Machine for Cutting Pinion Rod

The type of machine used by the Meisselbach-Catucci Manufacturing Co. for cutting pinion rod is shown in Fig. 17. This is a machine of the hobbing type. The uncut rod is inserted at the rear end *A* of the work spindle, and it feeds automatically through the spindle past the hob *B*, which generates the teeth. A section of cut pinion rod is shown projecting beyond the hob.

At *C* is located a mechanism which feeds the pinion rod through the spindle, while the spindle and hob revolve at the proper ratio, as controlled by change gears at the opposite side of the machine. The feeding mechanism has a stationary worm about which a small worm wheel revolves, transmitting, through additional worm-gearing, a feeding motion to serrated rolls between which the pinion rod passes. The hob may be adjusted axially in order to centre a tooth relative to the pinion rod when the number of teeth in the latter is small.

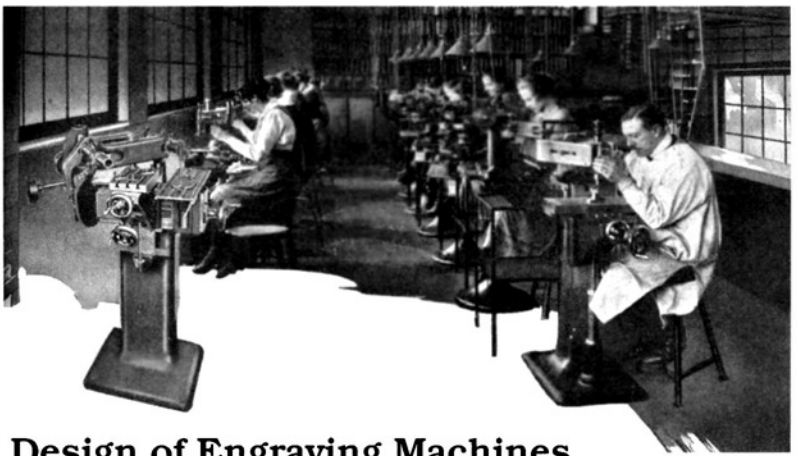
This hob takes a very light topping cut; that is, it removes a slight amount of stock from the tops of the teeth in order to finish the outside concentric. This is important, because when the pinion rod is afterwards placed in the screw machine it is gripped by the outside. Pinion rod having helical or spiral teeth may be cut on this machine. Provision is made for setting the hob to the angle required, by swivelling the head that carries the hob spindle.

Drawn Pinion Rod

Cold-drawn pinion rod is produced by methods that, in a general way, are practically the same as the methods employed for making cold-drawn rods or other sections. Care has to be exercised in determining the various reductions and annealings, in order to obtain the correct shape of tooth and size of rod, as well as the most suitable temper in the finished rod, for obtaining good cutting qualities. A.B. & J. Rathbone, of Palmer, Mass., U.S.A., manufac-

ture drawn pinion rod in brass up to 1 1/8 inch in diameter, and in steel up to 1 inch in diameter. This drawn rod can be supplied in lengths varying from 6 to 12 feet, according to diameter. The Rathbone process of drawing is said to compress the metal and give a smooth hard finish to the wearing surfaces.

This drawn pinion rod is used in the manufacture of clocks, watches, speedometers, gas meters, water meters, and electric meters, moving picture machines, typewriters, adding machines, slotting machines, mechanical toys, and many other devices.



Design of Engraving Machines

Pantographic Mechanisms – Mounting, Adjustment, and Drive for Cutter Spindle – Cutters Used – Different Types of Engraving Machines

BY L. B. – MACHINERY MAGAZINE – MAY 22, 1924

The term "engraving machine" as here used is applied to machines for reproducing a design, or some combination of letters or figures, from a suitable master at the same or a reduced scale, where a cutting tool is guided in two directions by grooves in this master. Such a machine consists of the frame and the following principal units: A table for receiving the master or copy; a table for locating the work piece; a cutting tool arranged, as a rule, to rotate, and equipped with bearing, drive and axial adjustment; and a mechanism for transmitting the movement from the master to the cutting tool.

The transmitting mechanism from the master to the cutter is, as a rule, a pantographic system of which three forms are shown in Fig. 1 at *A*, *B* and *C*. The point where the system is suspended is at *a*; *f* is the tracing stylus, and *s* the cutter

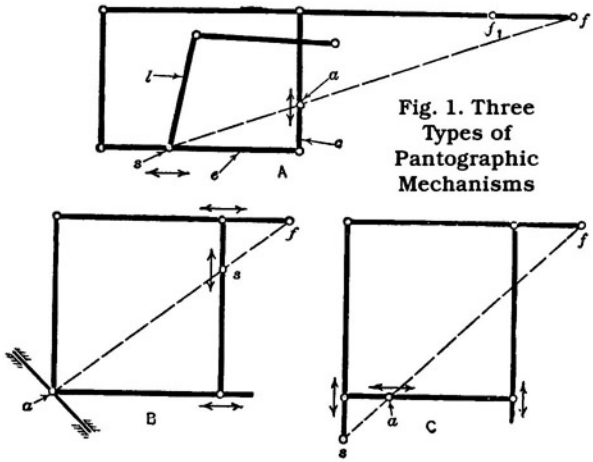


Fig. 1. Three Types of Pantographic Mechanisms

spindle. Arrows beside the different joints indicate the adjustments which have to be made for a different ratio of reduction. In order to attain an exact reproduction, it is necessary that in each position of the pantograph the three axes *a*, *f*, and *s* remain in a single plane, parallel to each other, and at a distance corresponding to the desired ratio of reduction. This ratio depends on the proper adjustment along the arms of the pantograph. Opposite sides of the parallelogram must be of exactly the same length, and the three axes *a*, *f* and *s* should be perpendicular to the plane of the parallelogram.

In view of the extensive application of engraving machines in both the machine-building field and numerous other industries, the information in this article will doubtless prove of interest and value to many manufacturers utilizing engraving machines. The principles underlying the operation of different designs of engraving machines are explained, and information is included on the different types of cutters and machines that are employed in Continental practice.

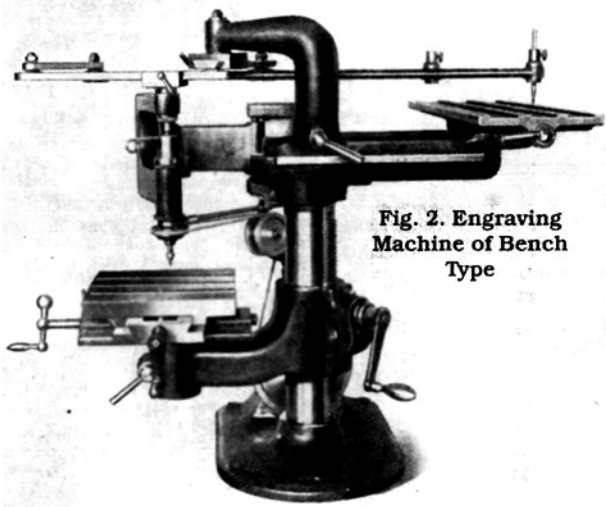


Fig. 2. Engraving Machine of Bench Type

Vibrations caused by the cutting pressure should be eliminated by a stiff construction of the members and a good design of the joints. The pantograph mechanism, however, should move easily in order not to fatigue the operator guiding it. The cutting spindle at *B* and *C* is supported by the pantograph, while the pantograph represented at *A* only transmits the movement to the cutting spindle, which is carried separately by two jointed links. The ratio of reduction between the work and pattern obtained with a pantograph such as shown at *A* may be varied from 1 to 1 down to any smaller scale due to the arrangement of the pantograph mechanism. For a reduction between work and pattern of from 1 to 1 down to 1 to 2, the tracing stylus is removed to a second point f_1 to decrease the leverage. This arrangement results in an easy movement, as the cutter spindle and pantograph are kept separate.

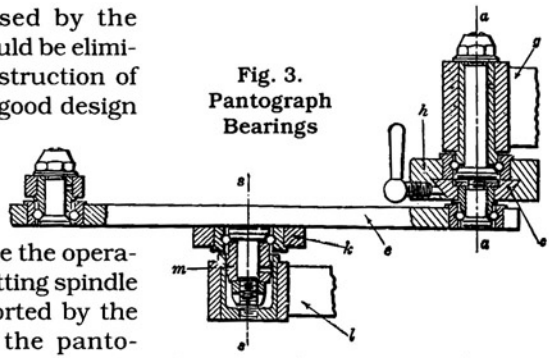


Fig. 3. Pantograph Bearings

The pantograph shown at *C* does not move quite so easily as the one just referred to, but it is more rigid. The reductions with such a pantograph may be varied from 1 to 1 down to 1 to 10. The construction at *A* is preferable for machines intended for light and medium work, while the design at *C* is especially suitable for heavy engraving cuts. At *B* the cutter *s* is arranged between the support *a* of the pantograph and the tracing stylus *f*, so that only a part of the cutting pressure, corresponding to the ratio of leverage, is transferred to the supporting shaft; this shaft, however, with the arrangements shown at *A* and *C* withstands, besides the thrust of the cut, the thrust taken by the stylus. Design *B* has greater stability, and is especially adapted for work requiring very heavy cuts. A disadvantage of this construction lies in the fact that the space for the work is limited to that between the tracing stylus and

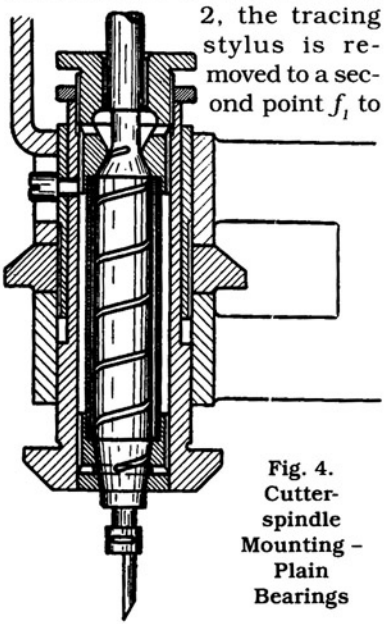


Fig. 4. Cutter-spindle Mounting – Plain Bearings

the supporting point; but it is very favourable in that a second axis may be arranged at right angles to the supporting shaft (as indicated in the diagram) so that the same machine may be used for the reproduction of plastic models. Milling out dies to obtain a reproduction of a model is an example of the work performed with the latter arrangement.

Fig. 3 is a section through the side e of the parallelogram shown at *A* in Fig. 1, with the support a moved to coincide with the centre line of the right-hand pivot. Usually one of the sides of a pantograph is mounted simply on plain pins of ball shape, which soon develop a small amount of play that is detrimental for precision work. To avoid this, all pivot shafts are arranged without play in adjustable single-row ball bearings of ample size. The small amount of movement desirable for equalizing any minute inaccuracy in manufacturing or assembling is provided by the ball-shaped bushing *m*, which, however, does not turn, but only oscillates and moves axially very slightly; consequently, wear is reduced to a minimum. The links or arms *e* and *c* of the pantograph are of trapezoid cross section, and the sliding members h and *k* of the pantograph carrier g and the cutter-spindle bearing are scraped to fit these arms accurately.

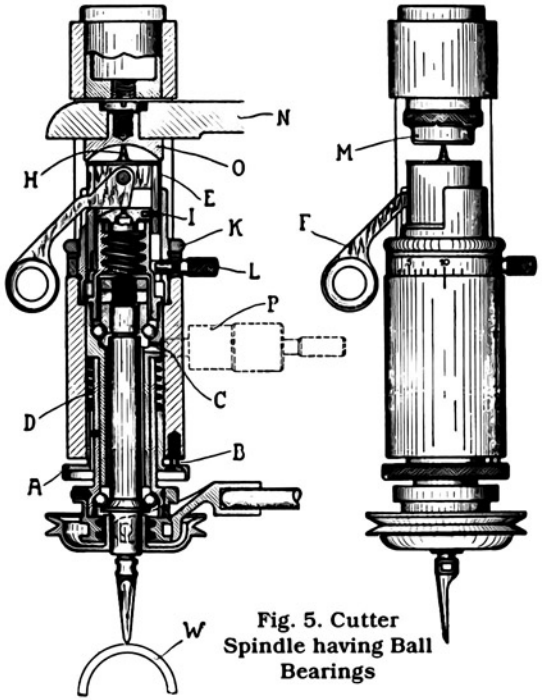


Fig. 5. Cutter Spindle having Ball Bearings

The Cutter Spindle

The mounting of the cutter spindle is a very important part of an engraving machine, because a satisfactory bearing must fulfil quite a number of requirements. The cutter journals should be without the slightest play, either in axial and radial directions, because the least amount of play would show in the engraving cut. At the same time, the frictional resistance of the bearing should be as low as possible, as a very high speed is

necessary for the narrow cuts generally taken. A cut 0.020-inch wide and a spindle speed of 10,000 revolutions per minute result in a cutting speed of only 52 feet per minute, while the finest of hair-line engravings required in the optical instrument, and watch industries have widths as small as 0.001-inch.

The drive for the cutter spindle should not transmit vibration to the spindle. At the same time, the spindle has to follow readily every movement of the pantograph without causing unusual belt tension. Finally, a sensitive axial adjustment of the cutter must be provided for regulating accurately and easily the depth of cut desired. A quick feed, besides the usual slow feed, proves advantageous for advancing and removing the cutter quickly, while an adjustable stop is very serviceable for limiting the dept of the cut.

Bearing for the Cutter Spindle

Experiments extending over a period of several years have demonstrated that the two bearings shown in Figs. 4 and 5 possess special merit. The bearing in Fig. 4 is a plain type, With two adjustable conical surfaces at opposite ends of the spindle. To ensure a constant stream of lubrication, a spiral groove has been cut in the spindle to carry lubricant from the lower to the upper bearing surface when the spindle is rotating. The oil having passed through the upper adjustable bushing, returns through channels into a reservoir surrounding the centre portion of the spindle, and flows through openings in the lower fixed bushing back again to the lower bearing of the spindle, thus completing the circuit.

Fig. 5 shows a spindle carried by two angular-contact ball bearings, so arranged that any slight wear may be taken up by adjusting two nuts. To lubricate the spindle, the complete bearing is removed from the carrier, as will be described more fully later, and a grease gun *P* is used to force grease through an open-

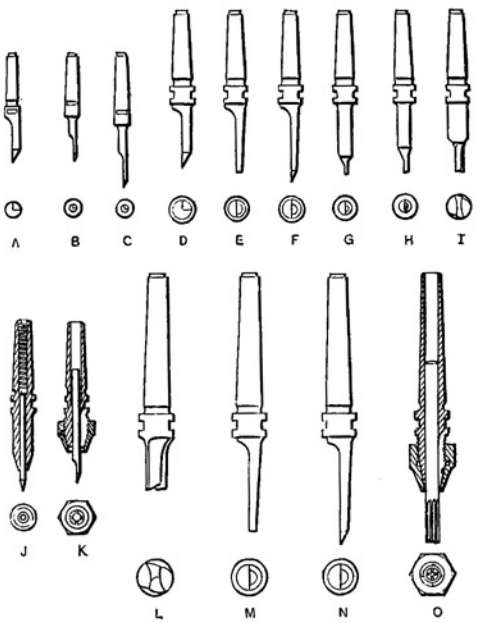


Fig. 6. Various Shapes of Engraving Machine Cutters

ing *C* into the bearing, completely filling the interior space. This need only be repeated every four to eight weeks. Besides the advantage of being practically independent of lubrication, a ball-bearing spindle does not need any clearance for an oil film, and may be employed at very high speeds without causing trouble.

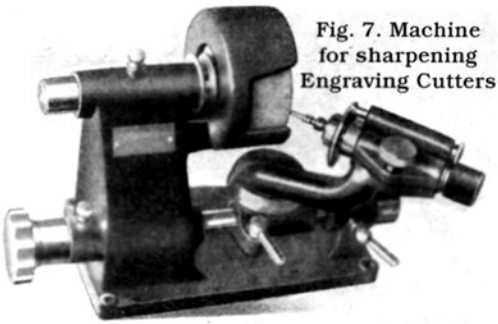


Fig. 7. Machine for sharpening Engraving Cutters

Drive for the Cutter Spindle

The driving of a spindle that is free to move at right angles to its axis, from a stationary shaft, has been done in different ways. Several short round belts may be employed with the sheaves located on the turning pivots of the links, or a single belt may transmit rotary motion from a driving pulley over guide rollers to the driven spindle, a rod being used to keep the guide rollers at a uniform distance from the driven spindle. The guide rollers are carried by a link fastened to the frame of the machine, and move at right angles to the axis of the spindle. The driving pulley is located perpendicularly above or below the central position of the guiding pulleys at as great a distance as possible.

The first arrangement has the disadvantage of using several short belts, which wear quickly and also cause vibrations by the passing of the connections over the sheaves. Endless belts cannot be used very well on account of the position of the shelves on the pivot pins of the links. With large movements, the second drive exerts a belt pull tending to bring the spindle back into the central position. The common construction of journaling the drive and spindle separately, with a connecting member between, removes the direct belt pull from the spindle, but does not avoid the transmission of vibrations; in fact, this arrangement may even be the source of an additional vibration synchronous with the number of revolutions, in case the axes are not mounted exactly in line, due to

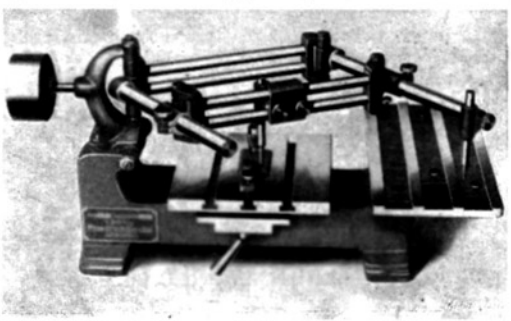


Fig. 8. Machine with Fixed or Non-rotating Cutter

Fig. 9. View showing Arrangement of Drive to Cutter Spindle

small inaccuracies in manufacturing or assembling.

In the design shown in Fig. 9, the spindle-driving problem has been solved in a simple manner, avoiding all objectionable features. The belt, on its course from the driving to the driven pulley and back again, passes over two guide pulleys at *D*, which are mounted on an arm *E*. The latter is pivoted to lever *B*, and a connecting rod *F* holds the idler sheaves in proper relation to the driven pulley; consequently, the total length of the belt is not varied by movements of the cutter spindle. Vertical adjustments of the cutter spindle cause a turning movement about an axis at *C*, which is located to cross the belt line so that no variations in length occur. The belt may be tightened by adjusting the connecting rod *F* through clamp screw *H*. The weight of the moving parts is compensated for by a counterweight. The shaft *A* is either driven by an electric motor mounted on the frame of the machine, as shown in the il-

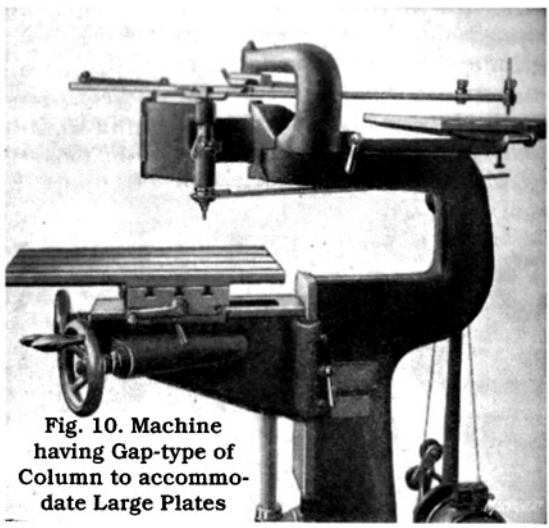


Fig. 10. Machine having Gap-type of Column to accommodate Large Plates

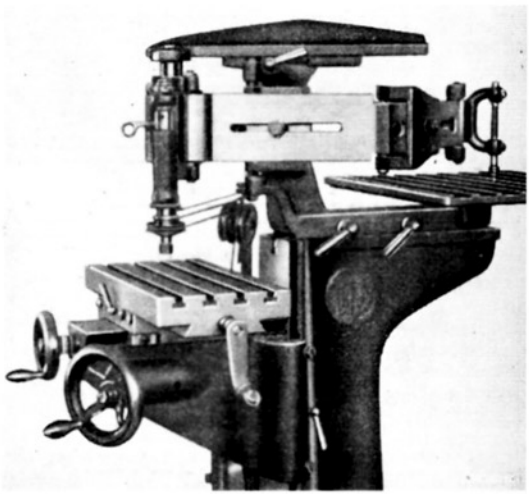


Fig. 11. Machine equipped with Pantograph of Type represented at C, Fig. 1

lustration, or by a belt drive from a counter shaft. Both belts are made endless to prevent vibrations due to the connecting joints.

Axial Adjustment for Cutter Spindle

The quick and slow adjustments obtained with the design shown in Fig. 5 are used to lower the cutter quickly on the part to be engraved and to regulate accurately the depth of cut. This construction may be used without change for engraving on flat work or for guiding the cutter to a pre-determined curvature. It will be seen that a lever *F* is pivoted on a pin fastened in a bushing *E*. In lowering the lever to the position shown in the illustration, a cam-like projection quickly depresses the bearing, which is held in contact with the lever by a spring *D*. By turning the lever *F* sidewise, a pin *I* in bushing *E* causes a relative movement in the screw connection, and a comparatively fine axial adjustment is the result.

To limit the depth of cut, a pin *L* is provided, which serves as a stop for the turning movement of bushing *E*; lever *F* may be adjusted sidewise after loosening nut *K*. Spring *D* rests against a knurled bushing *A*, which is held by a bayonet connection of the screw *B*, so that the bearing may readily be removed by lifting and turning bushing *A*. The parts for the axial adjustment, however, remain in the carrier, because, beyond the pin *I*, there is no connection with the bearing.

When engraving on flat surfaces, the spring pressure is transmitted by a point *H* to a counter holder *M* fixed on the carrier. For work on curved or angular surfaces, a curved or formed part *O* is used; this is carried by an arm *N* which is fastened to the frame of the machine. When the form *O* corresponds with the surface of the work *W*, engravings of even depth result without requiring an axial adjustment of the spindle. On account of the deflection of the cutter-caused by the unequal action of the working edges of a conical cutter op-

erating on inclined surfaces, this form of cutting tool should only be used for surfaces of a moderate inclination relative to the horizontal plane; as a rule, an angle of 30 degrees should not be exceeded.

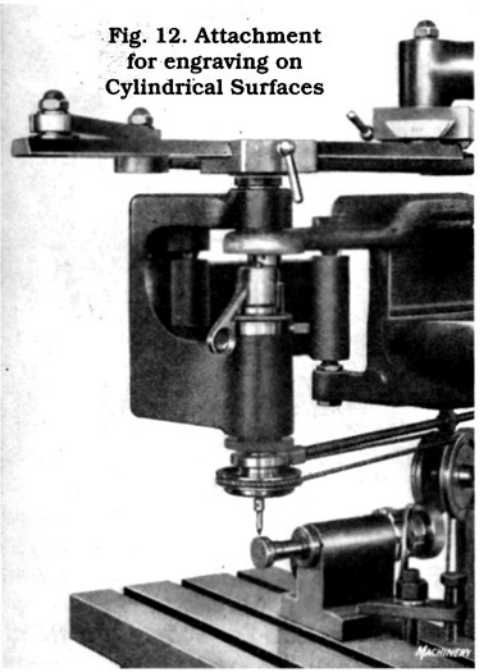


Fig. 12. Attachment for engraving on Cylindrical Surfaces

Cutters for Engraving

The cutters used in an engraving machine vary in form and shape according to the engraving to be done and the material to be worked upon. They are held either directly in the taper seat of the spindle or with an intermediate socket, or else they are formed of cylindrical pieces of drill rod and held in a special holder.

A variety of cutters is shown in Fig. 6. The cutters *G*, *H*, *I* and *L* are really milling cutters with one or two lips, and are used for heavy cuts in wood or metal. For hair-line engravings, which are used to a large extent in the instrument, optical, watch, and similar industries, the cutters *D* and *F* are preferable. The quarter cutter *D* has the advantage that the central edge has been made to coincide within close limits with the axis of the cutter; therefore it may readily be ground with the required relief on an ordinary grinding wheel and will still run true. To grind a half-round cutter *F* properly, a special grinding attachment is indispensable, as the position of the point cannot be located correctly otherwise.

To produce the very finest of hair-line engravings where the width cut by the point of the tool should be as small as 0.001-inch, it is necessary to eliminate the small unavoidable inaccuracies due to removing the cutter from its taper seat. To accomplish this, the complete spindle bearing is removed from the carrier, as has been described previously, and is inserted bodily in a holder of the special grinding machine shown in Fig. 7. Suitable graduations facilitate the setting of this holder for producing any desired angle of the conical point. The necessary relief of the cutting edge is ground by bringing the cutter up against the face of a cup wheel and turning it about its axis; this turn-

ing movement is discontinued when the cutting edge is in contact with the wheel, but before the surface below this edge has been ground back to a truly circular form. In this way a slight clearance is provided. A hand wheel at the left controls the feed of the cutter toward the grinding wheel. A grinding attachment on the engraving machine itself should not be used because of the grinding dust which will settle on the accurately finished surfaces of the engraving machine.

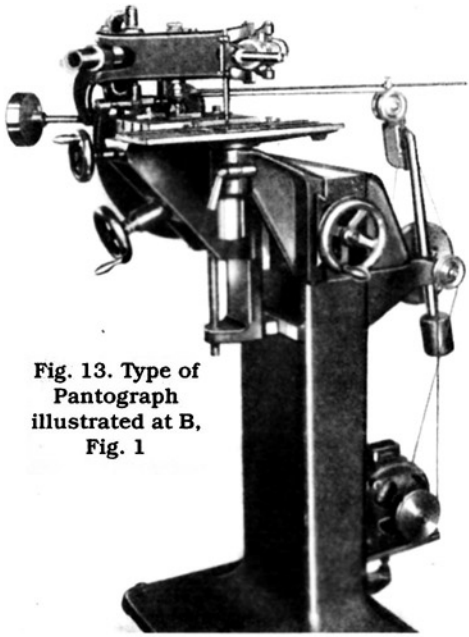


Fig. 13. Type of Pantograph illustrated at B, Fig. 1

Types of Engraving Machines

Engraving machines, like other machine tools, are made in different sizes and types to accommodate various classes of work. The machines referred to in the following, for which a number of patents are pending, are manufactured by the firm of Friedrich Deckel, Munich.

The plain pantograph shown in Fig. 8 is fitted with a fixed or non-rotating shaving tool. This machine is intended principally for etching hardened parts, such as gauges, tools, etc. A pointed rod *K*, Fig. 6, is guided over a surface previously covered with wax, thus exposing the desired design, which later is etched into the surface by treatment with acids. Having finished a design or any part of it, the etching tool may be removed from the work simply by lifting the tracing stylus, as the pantograph corresponds to the one shown at *B*, Fig. 1. The tracing stylus is fitted with a spring so that it will enter into the grooves of the master before the etching point touches the work; this spring also takes care of small irregularities in the surface of the work.

The bench type of engraving machine, shown in Fig. 2, is adapted especially for light cuts on parts of moderate dimensions, such as, for example, most of the work engraved in the optical and instrument trades. The bearing, drive, and axial adjustment of the cutter spindle correspond with the construction previously described, while the pantograph is the same as the

one shown at *A*, Fig. 1. The machine shown in Fig. 9 differs from the bench engraving machine (Fig. 2) only in having a larger range of action and in being mounted on a solid stand with a work table suitable for heavy parts.

For engraving large plates, the machine shown in Fig. 10 has been constructed with a frame of gooseneck form. This machine also has a large pantograph, and a long link and carrier for the cutter spindle bearing, thus permitting a considerable range of action. A large templet holder and an additional work table allow the full use of the increased range. Otherwise, the machine corresponds fully with the machines shown in Figs. 2 and 9. Fig. 11 shows the application of the pantograph shown at *C*, Fig. 1, on a heavy and ruggedly built engraving machine, which is capable of taking regular milling cuts.

All of the machines referred to, with the exception of the plain pantograph type, are constructed to mount, without further change, the attachment shown in Fig. 12. This attachment may be used for engraving on cylindrical surfaces, as shown, or for holding any parts requiring rotation to obtain different working positions. A pantograph corresponding to type *B*, Fig. 1, is shown in Fig. 13 applied to an engraving machine adapted for extremely heavy cuts. With such a pantograph, this machine is not only adapted for ordinary engraving and form milling work, but may also be used for reproducing plastic models, in the milling of dies.

Notes On The Correction Of Lathe Lead-Screws

By H.C.A. – Machinery Magazine – May 17, 1917

Apropos of a recent paper on the manufacture of screw gauges the writer was surprised to find that very few people had had any experience in correcting lead screws. The following notes are therefore put forward as perhaps being of general interest.

In going about the country at the present time one finds many firms have attempted screw gauge making without correcting the lead screw. It may be stated here and now, that it is an impossibility. They probably have several attempts and then give up. On the other hand in places the least expected a high degree of accuracy has been attained.

There are three stages in the manufacture of a screw gauge which call for a high degree of skill: (1) Cutting the thread in the lathe. (2) Hardening. (3) Lapping.

The last two operations are usually blamed for non-success but it is the considered opinion of the writer that the lathe work is where the errors are mostly

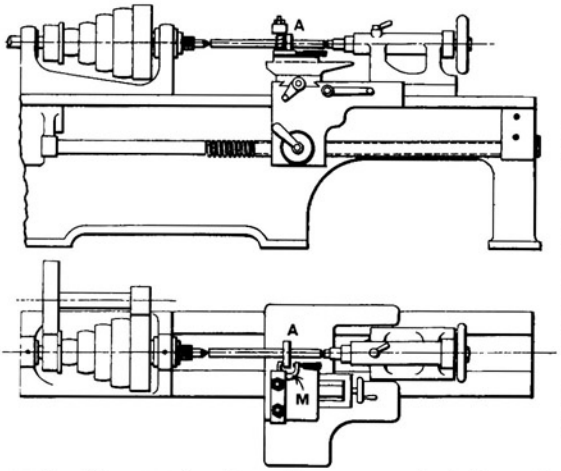


Fig. 1. Illustrating the set up for measuring the Pitch

made. The production of an accurate vee tool is comparatively easy, but no degree of skill or care can make up for an inaccurate lead screw. There are various ways of making a correction and one of the first things is to measure the inaccuracy, a rather difficult operation except by means of a special machine.

It is a waste of time to correct the lead screw of an old lathe. Select the best machine in the shop which is suitable for the work you want to produce, giving preference to the machine which possesses as many of the following points as possible: (1) A strong stiff screw. (2) A means of preventing absolutely any end play whatever in the lead screw (see later remarks). (3) A good relative position of the lead screw in regard to the centres of the machine to lessen the springing of the saddle. (4) A means of removing the split nut, which should be easily accessible. (5) A clutch drive with a reverse belt to prevent any necessity of disengaging the nut when at work.

A good class American toolroom lathe will probably have all these features except perhaps No. 4.

Measuring the Pitch Errors

In Fig. 1 is illustrated a set up for measuring the distance moved by the saddle per revolution of the face plate. A straight bar with a thin collar A, is set between the centres and the centres must be adjusted so that there is no end play. (Exception might be taken to this method on account of possible movement of the centres, but it is, after all, the way in which the work will be held). A rigid fixture clamped to the bed would be positively devoid of movement and theoretically correct, but the centre method reproducing a degree of working conditions is preferable.

A means of indexing the face plate should be provided and a micrometer *M*, set in the slide rest as shown. Then by proportioning the turns to the distance moved, measured accurately in 0.0001 inch will at once show errors in the screw. As the micrometer has to be screwed away from the collar and then adjusted back after each movement, beware of the play in the

micrometer unless the amount of error has been noted previously and allowed for.

When the lead screw was made it will have been subject to errors from three sources.

(1) Error in pitch which will be increasingly apparent the more turns the face plate has, i.e. a pitch or progressive error.

(2) Errors due to the jump and spring of the cutting tool and the play in every part of the master-lathe even down to a pegged tooth in a change gear. If the change gears were cast ones of course the lead screw will be anywhere, and if cut, the wheels would have to gear tightly together, a condition seldom met with as the change wheel frame is never stiff by the very nature of its universality to as many sizes of wheels as possible.

(3) Error due to differences of diameter in the screw. For instance in the portion where the lathe had been mostly used and having slightly worn at a particular place or by being slightly bent.

There are two main errors to combat therefore, one which increases with the distance moved or progressive, the other local and perhaps periodic.

Progressive Pitch Error

Pitch error will be found to vary considerably in different lathes. Few screw gauges are more than 1-inch in length on the working portion, and the limits of pitch error usually allowed are about 2 in 10,000 either way. This means that in one inch the error must not be greater than 0.0002 inch or less than 0.0002 inch: and if the mean is,obtained will give good results. A greater error will be quickly perceptible if a correct gauge is put in the lathe and the tool run along the crests of the thread. It is worth noting that attention should be confined to a given portion of the screw only.

Having ascertained the error it will be invariably found possible to get out a set of change wheels which, not being exactly correct themselves, throw their error opposite to that of the lead screw, thus making it a form of differential screw.

For example, if the pitch of the lead screw, instead of .25 inch were .2493-inch the error is 0.0007 inch. If the gears were calculated out for, say, 0.2507 inch and could be obtained exactly, evidently the lead screw would cut an accurate 1/4-inch pitch thread.

This is equally easy to follow in the case of any pitch of thread, but unless the corrected gears are actually stamped upon the machine plate there is every chance of the work done being entirely lost in general use. Also for every screw that was cut special gears would have to be schemed out.

This makes no allowance for the

Local and Periodic Errors

which may be caused by (1) The change gears not being perfectly square or centric. (2) The leading screw being bent or not re-

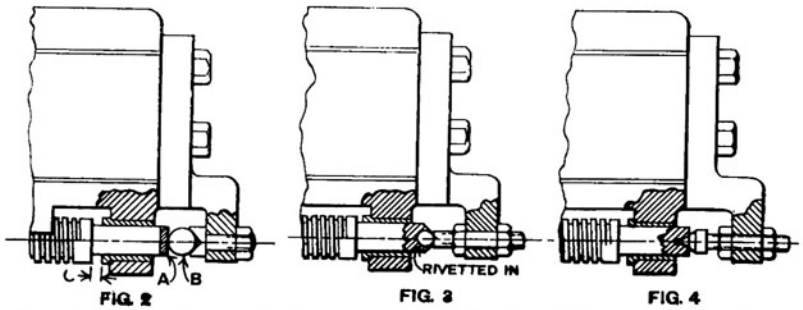


Fig. 2. Illustrating method recommended by the N.P.L. in their booklet on Screw Gauges. – Figs. 3 and 4. Illustrating two alternative methods

volving parallel to the saddle movement. (3) The end thrust not being perfectly taken up at each end.

In Fig. 2 is illustrated the method recommended by the N.P.L. in their booklet on Screw Gauges. *A* is a hardened steel plate fixed to the end of the screw after the collar has been made free of the bearing at *G*. *B* is a hardened steel ball about 1/2-inch diameter centred by a hollow hardened set screw held by a strong bracket clamped to the end of the bed.

Two alternative methods are shown in Figs. 3 and 4, but in the last case care must be taken to ensure that the centre is true with the axis of the screw, and for obvious reasons is the least reliable of the three.

There is a way of making a correction for both the periodic and progressive errors in one construction, but it is not easy and will prevent the lathe being used for other work. By referring to Fig. 5 we find *C* is a cam plate fixed to the lathe bed. The nut *N* is free to revolve slightly in either direction. To correct for the pitch error the roller *R* is moved up or down thereby moving the nut independently of the screw and differentially increasing or decreasing the pitch.

Societe Genevoise High Precision Lathe

A high-precision lathe specially constructed for cutting external threads for such work as screw gauges or small micrometer screws is made by the Soci-

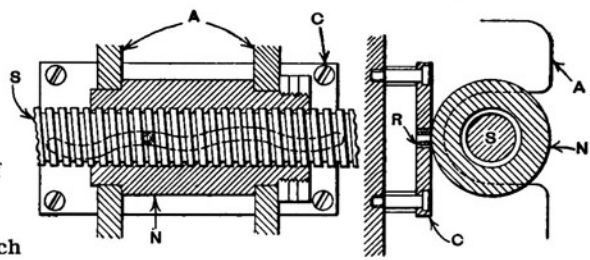


Fig. 5. Method of differentially increasing or decreasing the Pitch

ete Genevoise 78 Victoria Street, S.W., and is designed with a special view to accuracy in pitch. The work is held between two dead centres, means being provided for rotating the work without revolving the headstock spindle. The lathe bed forms two sets of slides, the one carrying the slide-rest being in front of that upon which the tailstock rests. This arrangement enables the lead screw to be placed centrally beneath the slide-rest, avoiding any tendency to twist the rest out of square with the bed.

Any error in the pitch of the lead screw is eliminated by means of a correction curve fitted at the front of the machine and just below the lead screw. This curve is in the form of a cam which has been carefully made after plotting the errors of the lead Screw.

The lead screw nut, instead of being rigidly fixed to the slide-rest, is free to swing radially. A projecting arm connects it with the correction curve below it and in travelling along the bed the movement given to it by the lead screw is modified by the radial movement given to the curve. By this means any error is reduced to something under + or – 0.0002 inch.

The arrangement for adjusting the depth of cut and the withdrawal of the tool differs from general practice inasmuch as a quick withdrawal motion is fitted so that at the end of the cut the slide itself is unclamped and withdrawn from the work without changing the position or setting of the micrometer screw. When so withdrawn the additional feed can be set and the whole slide can, by movement of the long lever, be brought back again to a fixed stop and there re-clamped. This is found to be much quicker in practice and a much easier method of accurately determining the depth of each successive cut.

Both transverse and longitudinal slides are fitted with micrometer screws of 50 threads per inch with index drums graduated to give a reading of 2/10000 inch.

All bearings are of steel, hardened and ground.

Making Precision Screws For Scientific Instruments

An Example Of American Practice

MACHINERY MAGAZINE – AUGUST 9, 1917

In ordinary machine shop practice the standard of workmanship is considered satisfactory if the error in machining does not exceed 0.001 inch. On tool-room work, where greater care is taken than in the average manufacturing operations, a considerably higher limit of accuracy may be attained, but

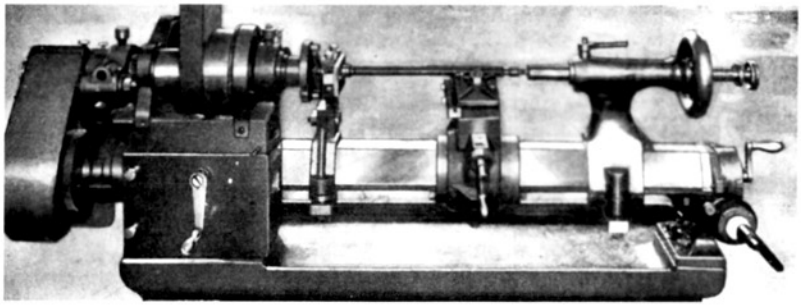


Fig. 1. Lathe on which Preliminary Screw Cutting Operation is performed. It is of the Pittler type, but has been furnished with Special screw Gearing and Auxiliary Equipment

highly skilled toolmakers or wide experience will feel satisfied with a piece of work if they are sure that the limit of error is not over 0.0001 inch. In any class of shop work, it is a waste of time, and entails a deliberate loss of production, to strive for a higher degree of accuracy than is absolutely necessary, and the limits referred to for the manufacturing plant and the tool-room have been found to mark the boundary line between products that will give good service and those with which unsatisfactory results are likely to be experienced through difficulty in assembling, failure to operate properly, and similar troubles.

In making parts of scientific instruments, the case is very different, because here errors which would be quite insignificant in any commercial work may be multiplied as a result of conditions under which the instruments are used, so that data obtained with inaccurate apparatus would be highly misleading instead of a means of furnishing valuable information. A case in point is seen in astronomical and physical instruments – say, micrometers and comparators. Micrometers are used in connection with astronomical telescopes for determining the distance between the stars, or with spectroscopes for locating the position of spectrum lines, etc., the measurements being made directly with the micrometers, while with comparators or measuring machines the measurements are made on photographs of the stars or spectra. When using a comparator, the cross-hair of a microscope on the comparator is first centred on one star, after which the position of the microscope is noted. It is then moved by means of a screw until the cross-hair is centred on another star; and the distance between these two stars on the photograph is determined by the number of turns made by the screw. The actual distance between the two stars is then calculated from these data and other information at the disposal of the astronomer. Very little thought will make it apparent

that in order to secure data that constitutes a reliable basis of calculation, the comparator screw must be of the highest accuracy, because a slight error in setting the instrument is multiplied many times, due to the great distance of the stars from the telescope and the multiplication of an error of arc with increase of distance from the centre.

Realizing the importance of this point, instrument makers and scientists have given a great deal of thought to the development of methods for eliminating error in screws, and have developed interesting methods of precision screw cutting described in this article.

Errors in screws may be either periodic or progressive. When a screw has a periodic error, it has what is commonly known as a drunken thread; the inaccuracy appears in every revolution of the screw, and usually proceeds in regular intervals from zero to a maximum error and back again to zero. In case the screw has progressive errors, it has the well-known errors of pitch, i.e., the pitch of the thread is not uniform throughout the entire length of the screw, so that when turned in a nut such a screw advances different amounts for different revolutions. From this it will be evident that a progressive error is entirely irregular.

In screw cutting, the operation of a lathe is chiefly governed by the familiar lead-screw and change-gears, and accuracy of the product of a screw cutting lathe is largely dependent upon the precision of its lead-screw and gears and the straightness of the lathe bed. So far so good, but the man who starts making a study of methods of precision screw cutting will eventually ask himself the question, "Where did the first lead-screw come from and what is responsible for its accuracy?" There are various methods of originating screws, and for the purpose of this article it will be satisfactory to describe one employed by the late C. Reichel a celebrated instrument maker of Berlin. This method consisted of taking wire of uniform diameter and, say, exactly one millimetre in size, which was closely wound and soldered on to a mandrel and mounted on the lathe spindle. The lathe used for this work was what is known as a "sliding mandrel lathe," and this type of machine is still in use in instrument shops for chasing short threads. Mr. Reichel then made a multiple thread cutting tool of the chaser type, which had the teeth very accurately spaced, and proceeded with this to cut down the wire to form a screw thread.

The cutting tool was held stationary in the slide-rest, and a block of hard wood, also held stationary on a separate support, formed the nut or guide for the screw mandrel, the cutting tool and nut being 180 degrees apart. When the lathe was slowly run forward, with the cutting tool in contact with the wire thread, it

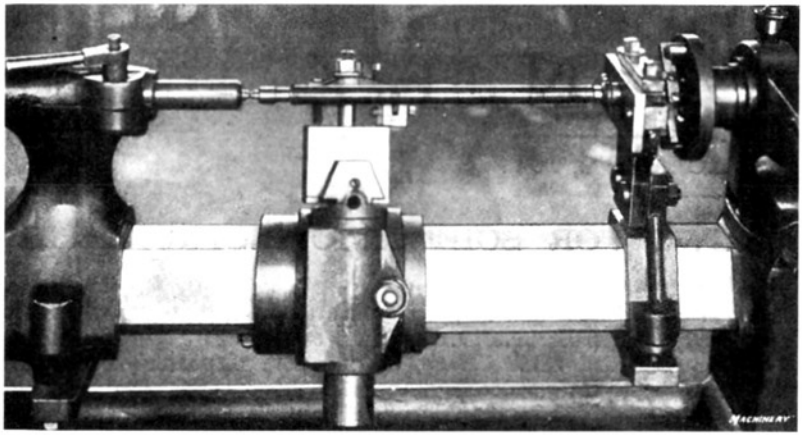


Fig. 2. Close View of Tool Work and Work-holding Device taken from Back of Machine

was observed that the tool did not touch uniformly, but showed a wobbling tendency in the thread, and usually touched one high spot in each revolution. The multiple tool was the means of correcting both periodic and progressive errors that could not have been eliminated if the work had been done with a single-pointed tool. After correcting errors in this screw, it was used as a master from which other screws were cut. In all precision screw cutting provision of accurate concentric bearings on the screw is of just as much importance as the cutting of an accurate thread, and the nut must be fitted to the screw with the greatest care.

It will be of interest to refer at this time to the way in which periodic or progressive errors are developed while cutting thread. In both cases, a variety of causes may be responsible for the trouble, but as a general thing the periodic error is due to eccentricity of the lathe spindle or to lack of uniformity in the gearing on the lathe, which is a result of inaccuracy on the gear-cutting machines. The errors in the gears become effective at those intervals where the teeth in which there are errors come into mesh, and at such times an error is introduced in the screw cut on the lathe through lack of uniformity of movement of the lead-screw on the lathe. Production of screws with a so-called progressive error or errors of pitch is harder to explain than the screw with the periodic error, because the discrepancy follows no fixed rule. This error may be due to inaccuracy in the gears, to lost motion in machine members, lack of straightness of the lathe bed, or to numerous other causes.

Practice in Screw Cutting

In making precision screws, observance of the following points is a matter of great im-

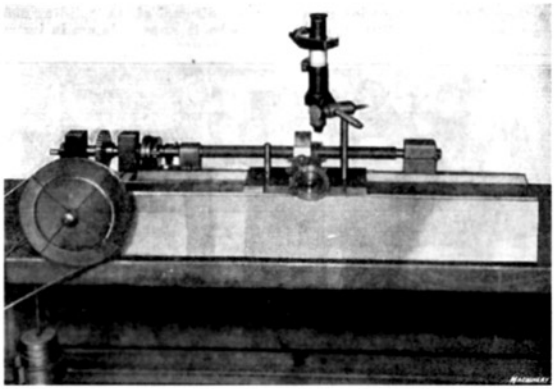


Fig. 3. Screw Recutting Machine designed to operate on Principle shown diagrammatically in Fig. 4. Particular attention is called to Bearings for supporting screw to be recut, and Special Coupling between Work and Machine Spindle

portance if accurate results are to be obtained: (1) The steel must be fine grained and homogeneous. (2) After roughing out the thread the screw must be carefully examined to see that no defects in the steel have been exposed during the process of screw cutting. (3) The rough-cut screws must be put aside to "season" for several months so that they will take the full "set" developed through removal of the surface-skin from the metal, after which the finishing cuts may be taken with the assurance that there will be no further distortion. In one shop, the preliminary work of screw cutting is done on a lathe, of German manufacture, made by Pittler. However, the design of this machine has been considerably modified, and many details have been improved or entirely renewed to adapt the machine for the precision work for which it is now used. The provision of an accurate lead-screw and gearing are typical examples off the changes that were made. In cutting screws for astronomical or similar instruments, precautions must be taken to avoid the introduction of errors of such slight magnitude that they could be entirely disregarded on many classes of commercial work.

Reference to Figs. 1 and 2, which show a front view of the lathe on which the preliminary screw-cutting operations are conducted and a close view of the tool and work taken from the opposite side of the machine, respectively, will show that instead of setting up the work in the usual way, the screw is mounted on stationary centres, i.e., dead centres, and the cutting is done on the same bearings on which the screw is afterward used in the apparatus for which it is intended. Clamped to one end of the screw is a dog which engages the lathe spindle and provides for rotating the screw. It will be apparent that the chief reason for this method of procedure is that it ensures cutting the thread on the screw in accurate alignment with the bearings that have already been turned at the ends of the screw blank; in addition slight inaccuracies that might be

introduced in the screw as a result of belt pull and slight errors in the lathe spindle bearing are overcome. With the work set up in this way, the method of cutting the screw is practically standard, except that after roughing out the thread, the screw is set aside to season, as mentioned.

Recutting Machine for Removing Periodic Errors from Thread

Various means have been tried for eliminating the periodic error from screw threads, but the following method of recutting is among the most satisfactory. Credit for the development of this method is given to the late C. Reichel of Berlin; and the theory of this operation is best shown by reference to the chart presented in Fig. 4, Both curves show the way in which a periodic error in a thread runs from zero to a maximum and back again to zero during a period required for one revolution of the screw. After grasping the full significance of this fact, it was realised that by recutting the screw with a tool carried on a slide, the position of which could be governed according to the amount of correction required at different points on the thread, it would be possible to make the thread absolutely accurate. This result is obtained by the use of a nut, consisting of a single V-shaped point, which enters the thread. It will be seen that the nut is carried on a yoke that extends over from the slide, and different settings may be made, so that the nut, is placed 180, 90, or 45 degrees from the tool. Fig. 4 shows diagrammatically the conditions that exist when the nut is set 180 degrees from the recutting tool. Here it will be noticed that when the nut engages the screw thread at a point of maximum error, the tool lying opposite the nut engages the thread at a point where there is no error. Conversely, when the tool is at the point of maximum error, the nut is at a point where the error is zero. In this way the nut moves the tool slide along the bed and advances the tool to the work at a rate that is governed by the amount of error to be removed from the screw thread at the point where the tool is working. A counterweight, connected to the tool slide by a cord, relieves the screw thread and nut of much of the strain incident to moving the tool-slide along the bed of the machine.

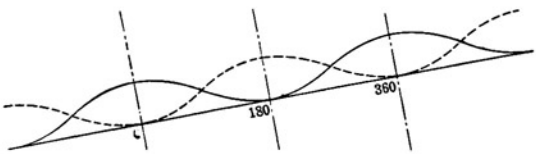


Fig. 4. Diagram showing Possibility of Designing Screw Recutting Machine that Automatically regulates Depth of Cut according to Error in Lead of Thread

A recutting machine operating on this principle is shown in Figs. 3 and 5; the best idea of its method of operation will be gathered from the end view, where it

will be seen that the nut is located at the back of the screw, and the cutting tool at the front of the screw to correspond with the conditions shown diagrammatically in Fig 4. When the nut is at a point of maximum error, the tool is opposite a point of zero error, and is clear of the work, so that no cut is being taken. After the screw has made one half turn, so that the nut comes to a point of zero error, the toolslide has advanced so that the tool is taking a cut of maximum depth. Of course for intermediate positions the depth of cut ranges between zero and the maximum. The amount of metal removed during this recutting operation is extremely small. Viewing the operation of the tool with the naked eye one would say that the tool was not in action, but when observed through a microscope provided on the machine for that purpose, one can easily see how the tool starts to take a very light cut, which gradually increases and leaves a fine dust of metal on the lip of the tool.

One traverse of the cutting tool over the screw, with the nut set at 180 degrees to the tool, results in reducing the error in the thread to one-half its previous magnitude. After taking this cut, the nut is transferred to the 90-degree position and a second cut is taken, which results in again dividing the error in half. Then the nut is set so that it is at 45 degrees from the tool, and a third cut is taken, which once more divides the existing error in half. In this way the final error in the thread is only 12 1/2 per cent of that which originally existed, and as the original screw-cutting operation performed on the Pittler lathe was done with every possible care, it will be apparent that the accuracy of the finished screws is extremely high. As a matter of fact, screws are sold under a guarantee that the error in lead will at no point exceed 0.001 millimetre, i.e., 0.00004 inch from the path of a theoretically accurate helix, although far greater accuracy has been secured. The attainment of such a degree of precision will certainly be appreciated by every skilled mechanic.

To obtain such a degree of accuracy calls for a machine operating on the principle described, that is, making the periodic error at one side of the screw adjust the position of the tool to eliminate the error at the opposite side. But this would be inadequate if great care were not taken in constructing the machine and setting up the work to obviate lost motion and other troubles of a kindred nature. In building the machine, great care was taken to obtain the best possible fit for all bearings and slides, and have the guides absolutely straight. In setting up the work, corresponding care is taken, the ultimate object being to bring the axis of the screw exactly parallel to the guides, and to eliminate every possibility of lost motion. Instead of being satisfied with mounting the

screw on centres, it will be seen that bearings are provided which are carefully fitted so that the accurately finished bearings at each end of the screw will be carried in them without chatter or vibration. On the spindle there is a faceplate to provide for driving, but the screw were driven through a dog, there is little doubt that strains would be developed that would result in errors, so that the accuracy of the thread would be impaired during the process of recutting instead of improved. As a substitute for the dog, it will be seen that a special form of coupling is provided between the lathe spindle and work. This coupling compensates for any lack of alignment and relieves the work of all strains that might be put upon it through the use of the usual form of driving dog.

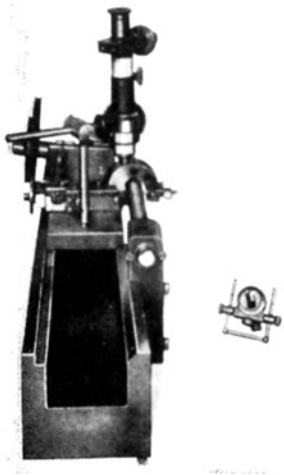


Fig. 5. End View of Machine shown in Fig. 3, showing Yoke that supports Nut and Tool

Lapping Screw to Polish Thread and Reduce Error

Before adopting the practice of recutting screws on the machine shown in Figs. 3 and 5 to eliminate the error, the screws were lapped in a machine of the type shown in Fig. 6. It will be seen that the machine is furnished with a universal joint that drives a chuck in which it carried the screw to be lapped. This machine is driven by an electric motor that transmits power by means of a belt and worm drive to a vertical shaft on which are mounted two sprocket wheels *A*. Located between these sprockets is a clutch, which may be engaged with either sprocket to provide for driving through the open or crossed chain to get forward or reverse rotation of the main spindle of the machine. The control of this clutch is effected by means of a small worm at the upper end of the main spindle, which drives disc *B* by means of a worm-wheel and spur gears.

Holes are drilled around the periphery of this disc, into which two stop-pins may be fitted; these pins are set to give reversal at the desired point. This result is obtained by having the pins strike lever *C*, which throws over the clutch between sprockets *A* and reverses the drive. When this is done, disc *B* runs back in the opposite direction until the other pin in the disc strikes lever *C* from the opposite side, when the clutch is thrown in the opposite direction and the machine once more reverses. The reservoir in which the screw rotates is filled with a mixture of oil and the finest grade of em-

ery. Closely fitted to the screw there is a long nut, which is supported by counterweight *D*. The nut runs up and down the screw with each reversal in direction of rotation; and by having its weight removed from the screw, there is no tendency to introduce unequal wear on the screw thread. A stirring device keeps the mixture of oil and abrasive thoroughly agitated. This consists of a number of small propeller blades mounted on a vertical shaft, which is driven by the same motor that drives the machine. In this way the lapping nut is constantly supplied with fresh abrasive, and the fine particles of steel and worn particles of abrasive are washed out of the nut. Any one who is familiar with the process of lapping a screw knows what damage would be done by allowing small steel chips to remain mixed with the abrasive material, and to avoid trouble from this source several strong magnets are suspended in the tank to collect these chips as fast as they are produced.

To investigate the accuracy of a screw throughout its full length is a tedious and laborious proceeding, and is usually left to the scientist who is going to use the instrument of which the screw forms a part. For instance, to test a screw for one of the small comparators of 3 1/4 inches or 80 millimetres range, employing the microscope method of testing, requires about a month of the observer's time.

In testing a screw in the laboratory, the work is usually done on the completed instrument; and a microscope of suitable magnifying power, having a fine wire (spider thread) in the eye-piece and an accurately divided-scale are employed The microscope may be carried on the slide, which is moved by the screw, or it may be held stationary on the frame of the apparatus and the scale placed on the slide. If the microscope is movable, the scale is placed on a stage below and carefully adjusted to be parallel with the axis of the screw. Suppose the pitch of the screw is 1 millimetre, the scale will be divided up into spaces of 0.1 millimetre. The microscope is focussed on the scale and adjusted so that the spider thread in the eye-piece will bisect a scale mark. If the screw thread has a graduated dial with 100 divisions and the microscope is moved to the next line on the scale, the reading on the dial should be ten divisions.

In moving the microscope from line to line on the scale, and observing the readings on the graduated dial, the screw is directly compared with the scale. Any discrepancy from the required readings on the dial for each corresponding movement of the screw indicates an error. But what about the error in the scale, and what about the errors that may be made in setting with the microscope? There are two uncertain factors to be figured with. The scale may be tested at the Bureau of Standards, so that the value of every scale division is known, and the error of setting

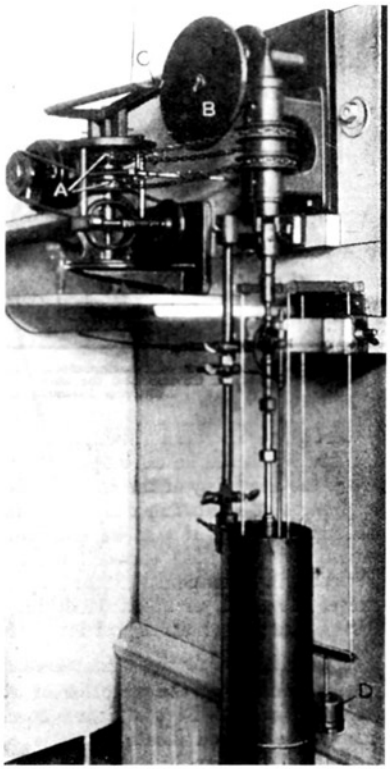


Fig. 6. Automatic Lapping Machine for imparting High Finish to Screw Thread after it has been Recut

may be eliminated by taking the mean of a number of readings; but anyone will see that testing a screw by this method is, at best, a slow and tedious proceeding, and requires great patience and a trained observer, so that it would not be suitable for use in a shop.

Another and quicker method that has been used is to mount the microscope and scale on two separate carriages, which are moved by the screw, as shown diagrammatically in Fig. 7. The microscope cross-hair is adjusted to a scale mark, and if the screw is then turned, both the microscope and scale should advance the same amount if the screw is free of errors, and the scale mark should remain in the same position in the field of the microscope. Any shifting of the scale mark indicates an error in the screw, but it will only show the difference in pitch of the screw at the two places on which the nuts engage.

A very accurate and reliable method of testing the errors of a screw, or of measuring any small unit of length, is based on the application of interference of light waves. It will be impossible in this article to enter into a detailed discussion of the theory of optical interference, which may be found in any standard book on optics. The instrument used for testing by this method is known as an interferometer, and it is the means of obtaining the most accurate results in length measurements; this method has become identified with the name of Prof. A. Michelson.

Fig. 8 shows the arrangement of optical parts of a simple form of interferometer. Light from a source *A* rendered approximately parallel by lens *B* is divided at surface *C* of the first glass plate into two beams, one passing on to mirror *F*, and the other being reflected to mirror *G*. After reflection from the mirrors, these beams of light are reunited at *C* and observed at *H* by a low-power telescope. The image from mirror *F* is seen in the direction

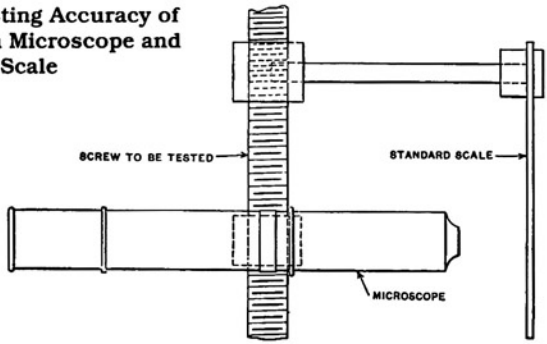


Fig. 7. Method of Testing Accuracy of Precision Screw with Microscope and Standard Scale

of *CG*, and attention is called to the fact that mirror *G* makes an angle slightly different from 90 degrees with *F*, thus fulfilling the conditions of interference. Plate *D* (compensator plate) is of exactly the same thickness as plate *C*, thus producing similar optical distances in both paths *CG* and *CF*. In the usual form of interferometer, mirror *F* is held stationary and mirror *G* is moved by means of a screw. If both the mirrors and plates are properly adjusted, there will be seen at *H* what are known as interference fringes, which have the appearance of bands of high lights and shadows.

By adjustment of the mirrors the space between two adjoining bands may be made any desirable distance, say two to five millimetres. If sodium light is used which has a wave length of 0.000589 millimetre, the space between two bands represents, one wave length, i.e., 0.000589 millimetre, or 0.000023 inch. If now the cross-hair of the telescope is adjusted to the centre of one band and mirror *G* is moved 1/2 wave length, or 0.000294 millimetre, the optical path *CGC* will be changed a full wave length and the next adjoining band will appear under the cross-hair. If the bands are adjusted, say, 5 millimetres apart; a travel of 5 millimetres in the telescope will be equal to a motion of the mirror of 0.000294 millimetre, or 0.0000116 inch, from which it will be seen what a high degree of accuracy is obtainable and that a one-millionth part of an inch can not only be estimated but actually measured.

Fig. 9 shows in diagrammatic form the appearance of the interference fringes in the eyepiece of the telescope when the interferometer is adjusted to space these fringes at intervals

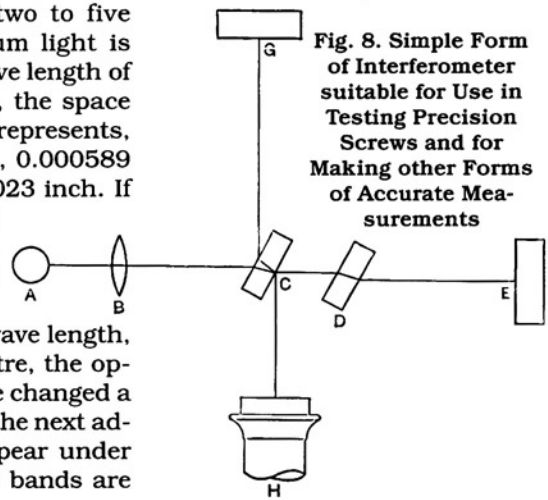


Fig. 8. Simple Form of Interferometer suitable for Use in Testing Precision Screws and for Making other Forms of Accurate Measurements

of 5 millimetres. By suitable adjustment, the fringes may be centred on scale graduations, but in order to provide for accurately measuring any given displacements, the telescope is provided with a micrometer, by means of which the scale can be moved in the eye-piece of the telescope. In this way the scale graduations can be brought back to the central position, and the necessary movement to so centre the graduations is indicated by the micrometer dial. Error in centring the scale graduations on the interference fringes is eliminated by taking the mean of a series of readings. In testing screws, the interferometer is used similarly to the microscope and scale, Fig. 7, but instead of measuring the unit of length on the scale, light waves are used and the number of interference bands are counted in the telescope while turning the screw a fixed amount.

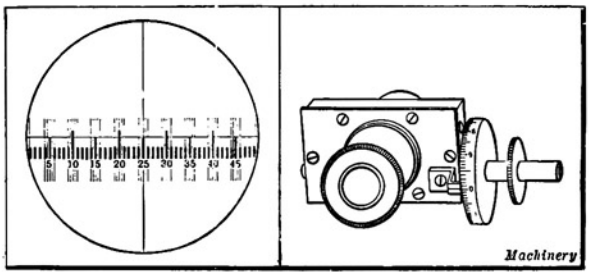


Fig. 9. Appearance of Interference Fringes and Scale in Eye-piece of Telescope; and Micrometer Head for Recentring Scale Graduation on Fringes

A more rapid method, provided by an application of the interferometer principle, is shown in Figs. 11 and 12; but probably a better understanding of the method of using this apparatus will be gathered from the diagrammatic view in Fig. 10, which shows the principle clearly. It will be seen that the equipment consists of a bed, in which are carried bearings for the screw to be tested. At the forward end of this bed there is a stand, on which are mounted two glass plates and one mirror, which receive light from the sodium gas flame *A* ; the rays of light are concentrated

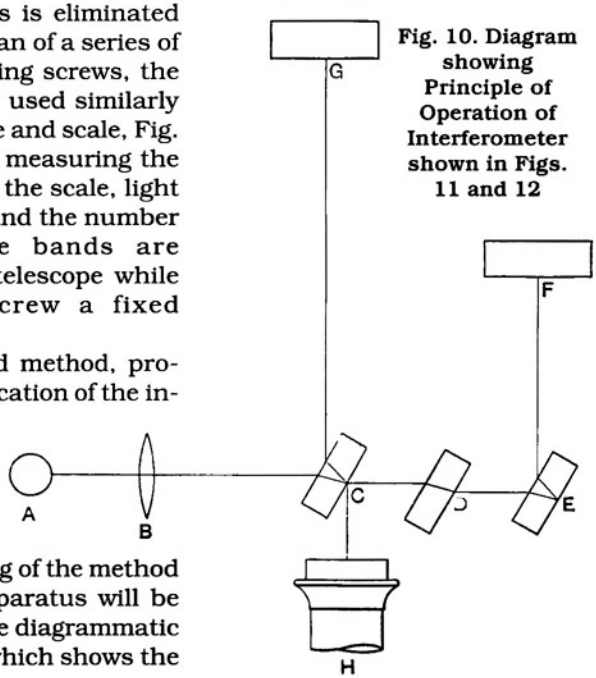


Fig. 10. Diagram showing Principle of Operation of Interferometer shown in Figs. 11 and 12

by means of a lens *B* set up in the stand placed between the light and the first glass plate *C*. Sliding along the bed of the machine are two bars, on each of which are supported mirrors *F* and *G*. These mirrors must be carefully adjusted so that they are exactly parallel with each other. Each mirror stand carries a nut that consists of a single point which is a close fit in the thread of the screw to be tested; and such adjustment of the apparatus is made that interference bands appear in the field of the telescope.

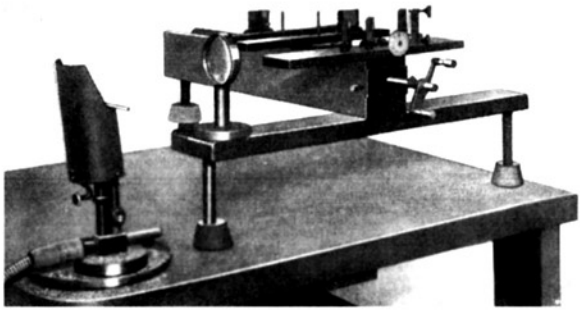


Fig. 11. Special Application of Interferometer Principle for rapidly Testing Accuracy of Precision Screws. This Test shows whether Error is Periodic or Progressive, and whether Maximum Allowable Error is exceeded, but Results are Qualitative rather than Quantitative.

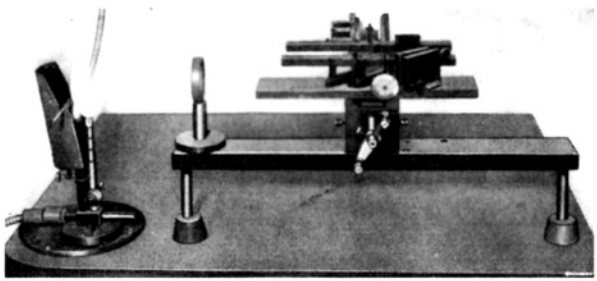


Fig. 12. Front View of Interferometer shown in Fig. 11. This show Ways on Bed and Bearings which support Screw to be Tested

Under these conditions, observation from the eye-piece of a telescope at *H* reveals the interference bands, which have the appearance of vertical bands of high light and shadow. As the handle at the front of the machine is turned, rotation of the screw causes the two bars supporting mirrors *F* and *G* to be traversed along the bed of tile machine, and in the case of a periodic error in the screw, this results in causing the central fringe to first move slightly away from a cross-hair in the field the telescope and then return to this cross-hair. In the case of a progressive error, the central fringe also moves away from the cross-hair in the telescope, but with an error of this kind the fringe may continue to move away instead of returning to the starting point. From the distance through which the interference fringes move in the field of the telescope, the observer is able to

estimate the amount of error that exists in the screw thread, and if this error does not exceed that which is allowable, the screw is pronounced ready for use. If, on the other hand, a considerable error is discovered, it is necessary to correct this error or make a new screw. The advantage of this method of testing is that while it is not quantitative, that is, does not show the actual amount of error that exists at each point on the screw thread, as in the method previously described, it does afford a rapid method of determining whether the maximum error in the screw exceeds that which is allowable. This is all that the instrument maker is interested in, and so the interferometer method is the means of saving him the expense of having men spend a large amount of time in testing the accuracy of each screw by the tedious micrometer-microscope method to which reference has been made.

Cutting a Lead-screw of Unusual Accuracy

Methods Used in Producing a Precision Screw About Four Feet Long with the Lead Accurate with 0.00004-inch in the Entire Length

BY W. G. – MACHINERY MAGAZINE – AUGUST 6, 1925

Precision screws of scientific instruments such as are used in spectrology and astronomy must be accurate to a degree that is unheard of in ordinary shop shop practice. This is necessary because very slight inaccuracies in the instruments themselves would be of far reaching importance, as, for example, in the process of measuring the spectrum lines when determining the impurities in metals by the spectrographic method; and in astronomical observations, slight inaccuracies would mean errors of countless miles. At the plant of the Gaertner Scientific Corporation of America, many types of scientific instruments are made, and these are usually fitted with lead-screws, which must be true within 0.001 millimetre in the entire length. Expressed in inches, this means an accuracy of within 0.00004 inch in the entire length.

These screws were formerly cut by single-point tools, but are now milled. It was decided some time ago to construct a machine whereby this preliminary thread milling could be performed on a commercial basis on larger screws than heretofore. For scientific purposes, the total length of the screw is not important – only the lead – but in commercial screws the total length must also be accurate. It is intended that the new machine shall cut screws up to 1 metre (39.37 inches) long. Such screws will find many applications in chemical, physical, metallurgical, and similar laboratories, and in as-

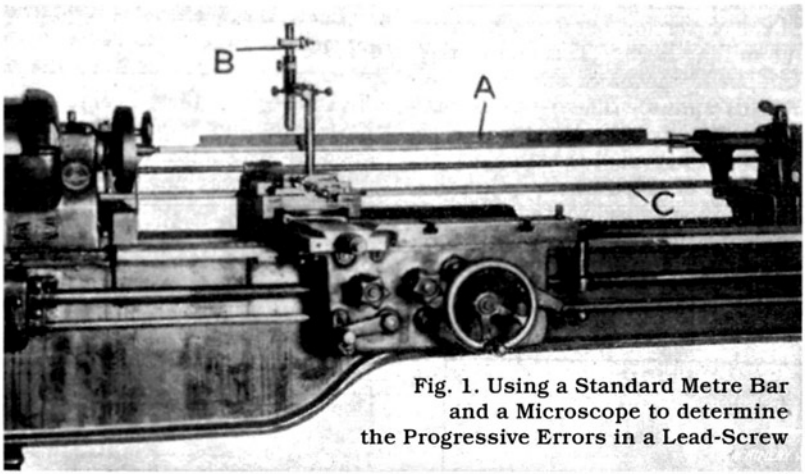


Fig. 1. Using a Standard Metre Bar and a Microscope to determine the Progressive Errors in a Lead-Screw

tronomical observatories, where delicate measurements requiring the greatest accuracy are necessary.

This machine also will require a lead-screw that is accurate in the lead within 0.001-millimetre in the entire length. The milling of this thread has already been done, and the methods followed in doing it will be described in this article. The milling alone consumed 480 hours. The screw is 1 metre 20 centimetres long (47.244 inches), 45 millimetres outside diameter (1.7716 inches), and has a pitch of 2 millimetres (0.0787-inch). The sides of the threads form an angle of 50 degrees with each other. The screw was made from a 2-inch bar of alloy steel, which was first turned and ground to the proper diameter.

Correction Bar that Compensates for Inaccuracies

The lead-screw for the new machine was cut in a lathe on which a thread-milling head was mounted on the tool slide. Before the operation could be performed, however, it was necessary to determine the accuracy of the lead-screw in the lathe, the straightness of the ways, the trueness of the gears and bearings, and the concentricity of the spindle rotation, as these four elements govern the accuracy of any screw cut in a lathe; corrections were then made for any errors. To compensate for errors in the lead-screw of the machine, a correction bar was produced which advanced or retarded the carriage certain amounts corresponding to the errors, as it was fed along the bed.

Progressive errors of the lead-screw were determined by employing a microscope and a standard metre bar, certified by the International Bureau of Weights and Measures, Paris, and the United States Bureau of Standards. Fig. 1 shows this metre bar mounted at *A* between

the centres of the lathe, and the microscope attached to the cross slide at *B*. At *C* is the correction bar made to compensate for the errors in the lead-screw.

With the lathe set up as shown and the hair line of the microscope coinciding with the first left-hand centimetre graduation on the metre bar, the lathe pulley was revolved the number of turns required theoretically to advance the carriage exactly one centimetre. Then the error of the lead-screw for that length was determined by observing the position of the microscope hair line relative to the next centimetre graduation on the metre bar. Lines were scribed on the stationary headstock and on the spindle to determine readily the exact number of revolutions given to the spindle. This examination was continued for the whole length of the metre bar. Readings were taken ten times, and the errors averaged. At the end of each test the pulley was revolved back, so that in taking every reading the same gear teeth were always in mesh at the same points along the bar. Little details, such as undue thrust on the lead-screw, were discovered and corrected. The ways were corrected by scraping.

After the errors of the lead-screw had been determined, the correction bar was made by first laying out on centimetre. graduations spaced along the bar, amounts that would compensate for errors in each centimetre length of the lead-screw. The edge was then filed from graduation to graduation, as shown exaggerated at *A* in Fig. 2. When the machine was set up, a lever was given transverse movements by this compensating edge, and because the errors in the lead-screw were in a longitudinal direction, the movements of the correction lever had to be translated into longitudinal movements for the milling cutter. Consequently, all amounts laid out on the graduations of the correction bar had to equal the actual errors of the lead-screw at the different points, multiplied by the ratio of the translating leverage. This ratio was 10 to 1. All amounts thus determined were considered as minus errors; that is, if the greatest plus error was 0.004 millimetre the edge of the bar was considered to correspond with that error. Then a minus error of 0.002-millimetre was marked 0.006-millimetre from the edge of the bar, and if there was no error at any graduation, that graduation was marked 0.004-millimetre from the edge.

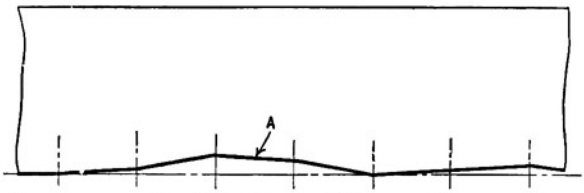


Fig. 2. Diagram showing the Curved Edge of the Correction Bar

The thread-milling head

shown mounted on the cross slide at *D*, Fig. 5, was developed especially for the machine now used for cutting precision screws. It is driven by spiral gearing from shaft *E*, and supports the milling cutter on the rear side of the work, so that the screw was milled as it revolved upward, the cutter rotating downward where it came in contact with the screw. The cutter head is free to move longitudinally in accordance with the contour of the correction bar. The slide on which the cutter head is mounted slides, free from friction, on balls running in hardened steel guides, so that the movements of the correction lever are readily imparted to the cutter head.

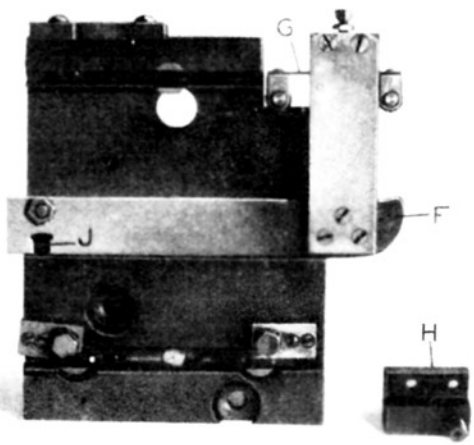


Fig. 3. Top View of the Base to which the Correction Translating Mechanism is attached

Fig. 3 shows the top view of the base to which the milling head slide is attached. The rounded end of lever *F* contacts with the compensating edge of the correction bar for imparting longitudinal movements to the milling head. This end of the lever is held in contact with the bar by means of spring *G* and the two rollers connected by this spring. These rollers run on the rear edge of the bar. The opposite end of lever *F* is pivoted on a stud, as shown. When the attachment is assembled, the shank of block *H* is engaged in slot *J* of the compensating lever, and block *H* is attached to the slide of the milling head. Hence, transverse movements imparted to the feeler end of lever *F* are translated into longitudinal movements of the miller head by means of slot *J* and block *H*. Block *H* can be seen located at *Y* in Fig. 5.

The design of the milling head can be better understood from Fig. 4, which shows it on the machine on which it is ordinarily used. All guards for the gears were removed when this photograph was taken. A 1/4 h.p. motor furnishes power for driving the milling head, work, carriage, and pump. This machine is also equipped with a

correction bar which compensates for errors in its lead-screw.

In milling the thread, eight cuts were taken for the entire length, each cut requiring about 60 hours, so that the total time consumed was about 480 hours.

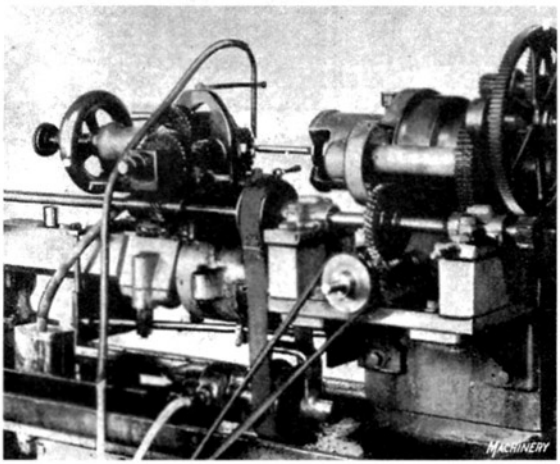


Fig. 4. Cutting a Small Precision Screw by the Use of the Special Milling Head

After a cut was started, the machine was not stopped until the operation had been completed and so it was necessary to run the machine day and night. The work rotated at a speed of only 10 revolutions per hour or one every 6 minutes, while the cutter speed was about 35 revolutions per minute. The cutter was 2 1/4 inches in diameter and was resharpened before each cut. At the beginning of the final pass no stock was removed by the cutter, this pass being made only to remove excess stock due to cutter wear on the preceding pass. From Fig. 5 it will be seen that a follow-rest was used to support the front side of the screw in order to prevent even slight bending. Cutting lubricant was generously supplied to the cutter.

In work of such precision, even comparatively slight differences in temperature would affect the accuracy of the screw, and so the work had to be performed at a season when the temperature could be best controlled. Hence the thread was milled during the months of November and December. An enclosure of asbestos board and wood was built around the machine and a constant temperature of about 74 deg. F. maintained in this enclosure. Steam coils gave the major portion of the heat, but an accurate control was obtained by means of six incandescent lamps arranged under the bed, as shown in Fig. 5, and connected to a lighting circuit. The current delivered to the lamps was governed by a thermostat which operated a two-plate metallic type relay. Current for operating the relay was furnished by the dry batteries.

Eliminating Final Errors

Progressive errors have been eliminated in the lead-screw by means of the correction bar, but There are slight periodic errors

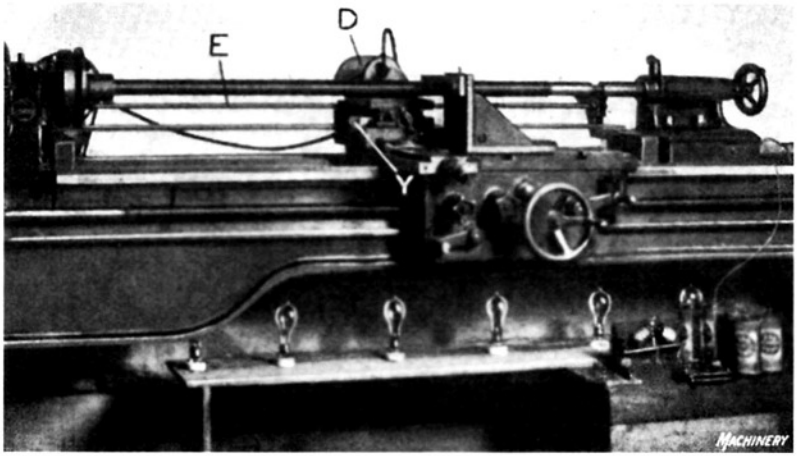


Fig. 5. Milling a Precision Screw with the Temperature controlled accurately by Means of Incandescent Lamps

which still remain to be removed by recurring in a machine that has not yet been constructed. The errors will be removed by using a singlepoint tool in a holder that will also contain a V-shaped point engaging the thread 180, 90, or 45 degrees from the tool. This point will act as a nut to move the tool slide along the bed and will engage the tool with the screw in such a way that the error will be removed at the place where the tool is working.

The amount of metal removed in this operation will be so small that it will appear as though the tool is not cutting, and so a microscope will be mounted on the machine carriage to observe the action. This operation, as performed on smaller screws, was completely described in the article previously referred to. At the end of the recurring, the screw will be lapped and then inspected by the interferometer method. Both the lapping and this inspection method have also been described in the previous article.

Thus far the lead-screw has cost about £275, including material, labour, and overhead costs, and it will probably cost a similar amount of money to complete it. However, when the machine in which it is to be used has been built, precision screws can be made from a curve-corrected lead-screw, and so correction devices will not be necessary or the individual precision screws produced in the machine. This will be an advantage of great importance.